

Robustness for Transient Problems

Truman E. Ellis and Jesse L. Chan

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Consider domain $Q = \Omega \times [0, T]$ with boundary $\Gamma = \Gamma_- \cup \Gamma_+ \cup \Gamma_0 \cup \Gamma_T$ where Γ_- is the spatial inflow boundary, Γ_+ is the spatial outflow boundary, Γ_0 is the initial time boundary, and Γ_T is the final time boundary. Let Γ_h denote the entire mesh skeleton.

Assume that boundary conditions are applied on the boundary $\Gamma_0 \subset \Gamma$. Recall that, for the ultra-weak variational formulation

$$b((u, \widehat{u}), v) = (u, A_h^* v)_{L^2(\Omega)} + \langle \widehat{u}, \llbracket v \rrbracket \rangle_{\Gamma_h \setminus \Gamma_0}$$

we can recover

$$\|u\|_{L^2(Q)}^2 = b(u, v^*)$$

for conforming v^* satisfying the adjoint equation

$$\begin{aligned} A^* v^* &= u \\ v^* &= 0 \text{ on } \Gamma_h \setminus \Gamma_0. \end{aligned}$$

Together, these give necessary conditions on the test norm $\|\cdot\|_V$ such that we have L^2 robustness (this gives robustness in the variable u ; for the first order formulation, conditions for σ must also be shown).

$$\|u\|_{L^2(Q)}^2 = b(u, v^*) \leq \frac{b(u, v^*)}{\|v^*\|_V} \|v^*\|_V \leq \|u\|_E \|v^*\|_V$$

Thus, showing $\|v^*\|_V \lesssim \|u\|_{L^2(Q)}$ gives the result that $\|u\|_{L^2(Q)} \lesssim \|u\|_E$.

1 Convection-Diffusion

Consider convection-diffusion

$$\begin{aligned} \frac{1}{\epsilon} \boldsymbol{\sigma} - \nabla u &= 0 \\ \frac{\partial u}{\partial t} + \boldsymbol{\beta} \cdot \nabla u - \nabla \cdot \boldsymbol{\sigma} &= f \\ \frac{\partial u}{\partial n} &= 0 \text{ on } \Gamma_- \\ u &= 0 \text{ on } \Gamma_+ \\ u &= u_0 \text{ on } \Gamma_0. \end{aligned}$$

Let $\tilde{\beta} := \begin{pmatrix} \beta \\ 1 \end{pmatrix}$ and $\nabla_{xt} := \begin{pmatrix} \nabla \\ \frac{\partial}{\partial t} \end{pmatrix}$, then we can rewrite this as

$$\begin{aligned} \frac{1}{\epsilon} \sigma - \nabla u &= 0 \\ \tilde{\beta} \cdot \nabla_{xt} u - \nabla \cdot \sigma &= f \\ \frac{\partial u}{\partial n} &= 0 \text{ on } \Gamma_- \\ u &= 0 \text{ on } \Gamma_+ \\ u &= u_0 \text{ on } \Gamma_0. \end{aligned}$$

We decompose the adjoint into three parts: a discontinuous part

$$\begin{aligned} \frac{1}{\epsilon} \tau_0 + \nabla v_0 &= 0 \\ -\tilde{\beta} \cdot \nabla_{xt} v_0 + \nabla \cdot \tau_0 &= 0 \\ \tau_0 \cdot \mathbf{n}_x &= \tau \cdot \mathbf{n}_x \text{ on } \Gamma_- \cup \Gamma_0 \\ v_0 &= v \text{ on } \Gamma_+ \\ v_0 &= v \text{ on } \Gamma_T \\ \llbracket v_0 \rrbracket &= \llbracket v \rrbracket \text{ on } \Gamma_h^0 \\ \llbracket \tau_0 \cdot \mathbf{n}_x \rrbracket &= \llbracket \tau \cdot \mathbf{n}_x \rrbracket \text{ on } \Gamma_{hx}^0, \end{aligned}$$

a continuous part with forcing term g

$$\begin{aligned} \frac{1}{\epsilon} \tau_1 + \nabla v_1 &= 0 \\ -\tilde{\beta} \cdot \nabla_{xt} v_1 + \nabla \cdot \tau_1 &= g \\ \tau_1 \cdot \mathbf{n}_x &= 0 \text{ on } \Gamma_- \\ v_1 &= 0 \text{ on } \Gamma_+ \\ v_1 &= 0 \text{ on } \Gamma_T, \end{aligned}$$

and a continuous part with forcing f

$$\begin{aligned} \frac{1}{\epsilon} \tau_2 + \nabla v_2 &= f \\ -\tilde{\beta} \cdot \nabla_{xt} v_2 + \nabla \cdot \tau_2 &= 0 \\ \tau_2 \cdot \mathbf{n}_x &= 0 \text{ on } \Gamma_- \\ v_2 &= 0 \text{ on } \Gamma_+ \\ v_2 &= 0 \text{ on } \Gamma_T. \end{aligned}$$

(The boundary conditions can be derived by taking the ultra-weak formulation and choosing boundary conditions such that the temporal flux and spatial flux terms $\langle \hat{u}, \llbracket \tau_n \rrbracket \rangle_{\Gamma_{out}}$ and $\langle \hat{f}_n, \llbracket v \rrbracket \rangle_{\Gamma_{in}}$ are zero.)

We can then derive that the test norm

$$\begin{aligned} \|(v, \boldsymbol{\tau})\|_{V,K}^2 &:= \min \left\{ \frac{1}{\epsilon}, \frac{1}{\mu(K)} \right\} \|\boldsymbol{\tau}\|_K^2 + \left\| \nabla \cdot \boldsymbol{\tau} - \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v \right\|_K^2 \\ &\quad + \left\| \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v \right\|_K^2 + \epsilon \|\nabla v\|_K^2 + \|v\|_K^2, \end{aligned} \quad (1)$$

Our goal is to analyze the stability properties of the adjoint equations by deriving bounds of the form $\|(v_1, \boldsymbol{\tau}_1)\|_V \leq \|g\|_L^2(Q)$ and $\|(v_2, \boldsymbol{\tau}_2)\|_V \leq \|f\|_L^2(Q)$. provides the necessary bound $\|v^*\|_V \lesssim \|u\|_{L^2(Q)}$.

Insert conditions on $\boldsymbol{\beta}$

Lemma 1.1. *For the above conditions on $\boldsymbol{\beta}$,*

$$\left\| \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v_1 \right\| \leq \|g\|$$

and since $-\tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v_1 + \nabla \cdot \boldsymbol{\tau}_1 = g$,

$$\|\nabla \cdot \boldsymbol{\tau}_1\| \leq \|g\|.$$

Proof. Multiply by $-\tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v$ and integrate over Q to get

$$\left\| \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v \right\| = - \int_Q u \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v - \epsilon \int_Q \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt} v \Delta v. \quad (2)$$

Note that

$$\begin{aligned}
-\int_Q \tilde{\beta} \cdot \nabla_{xt} v \Delta v &= -\int_Q \tilde{\beta} \cdot \nabla_{xt} v \nabla \cdot \nabla v \\
&= -\int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \int_Q \nabla(\tilde{\beta} \cdot \nabla_{xt} v) \cdot \nabla v \\
&= -\int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \int_Q (\nabla \tilde{\beta} \cdot \nabla_{xt} v) \cdot \nabla v \\
&\quad + \int_Q \tilde{\beta} \cdot \nabla \nabla_{xt} v \cdot \nabla v \\
&= -\int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \int_Q (\nabla \beta \cdot \nabla v) \cdot \nabla v \\
&\quad + \frac{1}{2} \int_Q \tilde{\beta} \cdot \nabla_{xt} (\nabla v \cdot \nabla v) \\
&= -\int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \int_Q (\nabla \beta \cdot \nabla v) \cdot \nabla v \\
&\quad + \frac{1}{2} \int_{\Gamma} \tilde{\beta} \cdot \mathbf{n} (\nabla v \cdot \nabla v) - \frac{1}{2} \int_Q \nabla_{xt} \cdot \tilde{\beta} (\nabla v \cdot \nabla v) \\
&= -\int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \int_Q (\nabla \beta \cdot \nabla v) \cdot \nabla v \\
&\quad + \frac{1}{2} \int_{\Gamma} \tilde{\beta} \cdot \mathbf{n} (\nabla v \cdot \nabla v) - \frac{1}{2} \int_Q \nabla \cdot \beta (\nabla v \cdot \nabla v) \\
&= -\int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \frac{1}{2} \int_{\Gamma} \tilde{\beta} \cdot \mathbf{n} (\nabla v \cdot \nabla v) \\
&\quad + \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v
\end{aligned}$$

Plugging this into (2), we get

$$\begin{aligned}
\left\| \tilde{\beta} \cdot \nabla_{xt} v \right\| &= - \int_Q u \tilde{\beta} \cdot \nabla_{xt} v + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\quad - \epsilon \int_{\Gamma_x} \tilde{\beta} \cdot \nabla_{xt} v \nabla v \cdot \mathbf{n}_x + \epsilon \frac{1}{2} \int_{\Gamma} \tilde{\beta} \cdot \mathbf{n} (\nabla v \cdot \nabla v) \\
&= - \int_Q u \tilde{\beta} \cdot \nabla_{xt} v + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\quad - \int_{\Gamma_-} \tilde{\beta} \cdot \nabla_{xt} v \underbrace{\nabla v \cdot \mathbf{n}_x}_{=0} - \int_{\Gamma_+} \left(\underbrace{\frac{\partial v}{\partial t}}_{=0} + \beta \cdot \nabla v \right) \nabla v \cdot \mathbf{n}_x \\
&\quad + \frac{1}{2} \int_{\Gamma_-} \underbrace{\beta \cdot \mathbf{n}_x}_{<0} (\nabla v \cdot \nabla v) + \frac{1}{2} \int_{\Gamma_+} \beta \cdot \mathbf{n}_x (\nabla v \cdot \nabla v) \\
&\quad + \frac{1}{2} \int_{\Gamma_0} \underbrace{n_t}_{<0} (\nabla v \cdot \nabla v) + \frac{1}{2} \int_{\Gamma_T} \underbrace{n_t}_{=0} (\nabla v \cdot \nabla v) \\
&\leq - \int_Q u \tilde{\beta} \cdot \nabla_{xt} v + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\quad + \int_{\Gamma_+} \left(- \frac{\partial v}{\partial \mathbf{n}_x} \beta + \frac{1}{2} \beta \cdot \mathbf{n}_x \nabla v \right) \cdot \nabla v \\
&= - \int_Q u \tilde{\beta} \cdot \nabla_{xt} v + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\quad + \int_{\Gamma_+} \left(- \frac{\partial v}{\partial \mathbf{n}_x} \beta + \frac{1}{2} \beta \cdot \mathbf{n}_x \frac{\partial v}{\partial \mathbf{n}_x} \mathbf{n}_x \right) \cdot \frac{\partial v}{\partial \mathbf{n}_x} \mathbf{n}_x \\
&= - \int_Q u \tilde{\beta} \cdot \nabla_{xt} v + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\quad - \underbrace{\frac{1}{2} \int_{\Gamma_+} \left(\frac{\partial v}{\partial \mathbf{n}_x} \right)^2 \beta \cdot \mathbf{n}_x}_{<0} \\
&\leq - \int_Q u \tilde{\beta} \cdot \nabla_{xt} v + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\leq - \frac{\|u\|}{2} + \frac{\left\| \tilde{\beta} \cdot \nabla_{xt} v \right\|}{2} + \epsilon \int_Q \nabla v (\nabla \beta - \frac{1}{2} \nabla \cdot \beta \mathbf{I}) \nabla v \\
&\leq - \frac{\|u\|}{2} + \frac{\left\| \tilde{\beta} \cdot \nabla_{xt} v \right\|}{2} + \epsilon C \|\nabla v\|^2
\end{aligned}$$

□

Lemma 1.2. *For the above conditions on β ,*

$$\|v\|^2 + \epsilon \|\nabla v\|^2 \leq \|g\|^2 + \epsilon \|f\|^2.$$

Note that $\boldsymbol{\tau} = \epsilon \nabla v$, so we already have control of $\|\boldsymbol{\tau}\|$.

Proof. Define $w = e^{T-t}v$ and note that $\frac{\partial w}{\partial t} = (\frac{\partial v}{\partial t} - v)e^{T-t}$ while $\nabla w = \nabla e^{T-t}v + e^{T-t}\nabla v$ and $\nabla \cdot (\boldsymbol{\beta}w) = \nabla \cdot (\boldsymbol{\beta})e^{T-t}v + \boldsymbol{\beta} \cdot e^{T-t}\nabla v$ and $\Delta w = e^{T-t}\Delta v$. Also, $\nabla_{xt}w = \frac{\partial e^{T-t}v}{\partial t} + \nabla e^{T-t}v = e^{T-t}(\nabla_{xt}v - v)$. Plugging this into the adjoint equation, we get

$$-\tilde{\boldsymbol{\beta}} \cdot \nabla_{xt}(w) - \epsilon \Delta w = u - \epsilon \nabla \cdot \boldsymbol{\sigma}$$

or

$$\tilde{\boldsymbol{\beta}} \cdot \nabla_{xt}(v) - v + \epsilon \Delta v = e^{t-T}(-u + \epsilon \nabla \cdot \boldsymbol{\sigma})$$

Multiply by $-v$ and integrate to get

$$\int_Q -\tilde{\boldsymbol{\beta}} \cdot \nabla_{xt}vv + v^2 - \epsilon \Delta vv = \int_Q e^{t-T}uv - \epsilon \int_Q e^{t-T}\nabla \cdot \boldsymbol{\sigma}v$$

Then

$$\begin{aligned} \|v\|^2 &= \int_Q e^{t-T}uv - \epsilon \int_Q e^{t-T}\nabla \cdot \boldsymbol{\sigma}v + \int_Q \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt}vv + \epsilon \int_Q \Delta vv \\ &= \int_Q e^{t-T}uv - \epsilon \int_Q e^{t-T}\nabla \cdot \boldsymbol{\sigma}v + \frac{1}{2} \int_Q \tilde{\boldsymbol{\beta}} \cdot \nabla_{xt}(v)^2 - \epsilon \int_Q \nabla v \nabla v + \epsilon \int_{\Gamma} v \nabla v \cdot \mathbf{n} \end{aligned}$$

Or

$$\begin{aligned} \|v\|^2 + \epsilon \|\nabla v\|^2 &= \int_Q e^{t-T}uv - \epsilon \int_Q e^{t-T}\nabla \cdot \boldsymbol{\sigma}v \\ &\quad - \frac{1}{2} \int_Q \underbrace{\nabla_{xt} \cdot \tilde{\boldsymbol{\beta}}(v)}_{=0} + \frac{1}{2} \int_{\Gamma} v^2 \tilde{\boldsymbol{\beta}} \cdot \mathbf{n} + \epsilon \int_{\Gamma_x} v \nabla v \cdot \mathbf{n}_x \\ &= \int_Q e^{t-T}uv + \epsilon \int_Q e^{t-T} \boldsymbol{\sigma} \cdot \nabla v - \epsilon \int_{\Gamma_-} v \underbrace{\boldsymbol{\sigma} \cdot \mathbf{n}_x}_{=\epsilon \frac{\partial v}{\partial n}=0} - \epsilon \int_{\Gamma_+} \underbrace{v}_{=0} \boldsymbol{\sigma} \cdot \mathbf{n}_x \\ &\quad + \frac{1}{2} \int_{\Gamma_-} v^2 \underbrace{\boldsymbol{\beta} \cdot \mathbf{n}_x}_{<0} + \frac{1}{2} \int_{\Gamma_+} \underbrace{v^2}_{=0} \boldsymbol{\beta} \cdot \mathbf{n}_x \\ &\quad + \frac{1}{2} \int_{\Gamma_0} \underbrace{v^2(-n_t)}_{<0} + \frac{1}{2} \int_{\Gamma_T} \underbrace{v^2}_{=0} n_t \\ &\quad + \epsilon \int_{\Gamma_-} v \underbrace{\nabla v \cdot \mathbf{n}_x}_{=0} + \epsilon \int_{\Gamma_+} \underbrace{v}_{=0} \nabla v \cdot \mathbf{n}_x \\ &\leq \|e^{t-T}\|_{L^\infty(Q)} \left(\int_Q uv + \epsilon \int_Q \boldsymbol{\sigma} \cdot \nabla v \right) \\ &\leq \left(\frac{\|u\|^2}{2} + \frac{\epsilon \|\boldsymbol{\sigma}\|^2}{2} + \frac{\|v\|^2}{2} + \frac{\epsilon \|\nabla v\|^2}{2} \right) \end{aligned}$$

□

2 Robustness for transient problems given spatial robustness

Suppose we have the transient problem

$$\frac{\partial u}{\partial t} + Au = f$$

with initial condition $u(x, 0) = u_0$. Suppose that DPG is robust under the ultra-weak variational formulation for the steady problem

$$(u, A_h^* v)_{L^2(\Omega)} + \langle \hat{u}, \llbracket v \rrbracket \rangle_{\Gamma_h \setminus \Gamma_0} = (f, v)$$

with test norm $\|v\|_V$. Then, can we show that

$$\|v\|_{V,t} := \|v\|_V + \left\| \frac{\partial v}{\partial t} \right\|_{L^2(\Omega)}$$

also leads to a robust upper bound of the L^2 norm by the DPG energy norm? I believe this may be possible. The adjoint equation for robustness for the transient problem gives

$$-\frac{\partial v}{\partial t} + A^* v = u$$

with $v = 0$ at $t = T$...