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Efficient C++ finite element computing with Rheolef: volume 2: discontinuous Galerkin methods

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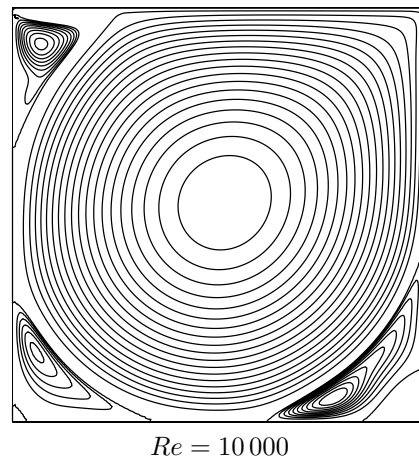
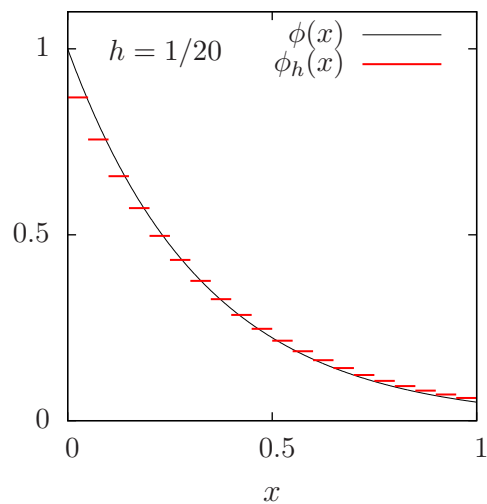
Efficient C++ finite element computing with Rheolef

volume 2:

discontinuous Galerkin methods

Pierre Saramito

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Notations

Rheolef	mathematics	description
d	$d \in \{1, 2, 3\}$	dimension of the physical space
dot(u, v)	$\mathbf{u} \cdot \mathbf{v} = \sum_{i=0}^{d-1} u_i v_i$	vector scalar product
ddot(sigma, tau)	$\sigma : \tau = \sum_{i,j=0}^{d-1} \sigma_{i,j} \tau_{i,j}$	tensor scalar product
tr(sigma)	$\text{tr}(\sigma) = \sum_{i=0}^{d-1} \sigma_{i,i}$	trace of a tensor
trans(sigma)	σ^T	tensor transposition
sqr(phi) norm2(phi)	ϕ^2	square of a scalar
norm2(u)	$ \mathbf{u} ^2 = \sum_{i=0}^{d-1} u_i^2$	square of the vector norm
norm2(sigma)	$ \sigma ^2 = \sum_{i,j=0}^{d-1} \sigma_{i,j}^2$	square of the tensor norm
abs(phi) norm(phi)	$ \phi $	absolute value of a scalar
norm(u)	$ \mathbf{u} = \left(\sum_{i=0}^{d-1} u_i^2 \right)^{1/2}$	vector norm
norm(sigma)	$ \sigma = \left(\sum_{i,j=0}^{d-1} \sigma_{i,j}^2 \right)^{1/2}$	tensor norm
grad(phi)	$\nabla \phi = \left(\frac{\partial \phi}{\partial x_i} \right)_{0 \leq i < d}$	gradient of a scalar field in $\Omega \subset \mathbb{R}^d$
grad(u)	$\nabla \mathbf{u} = \left(\frac{\partial u_i}{\partial x_j} \right)_{0 \leq i, j < d}$	gradient of a vector field
div(u)	$\text{div}(\mathbf{u}) = \text{tr}(\nabla \mathbf{u}) = \sum_{i=0}^{d-1} \frac{\partial u_i}{\partial x_i}$	divergence of a vector field
D(u)	$D(\mathbf{u}) = (\nabla \mathbf{u} + \nabla \mathbf{u}^T) / 2$	symmetric part of the gradient of a vector field
curl(u)	$\mathbf{curl}(\mathbf{u}) = \nabla \wedge \mathbf{u}$	curl of a vector field, when $d = 3$
curl(phi)	$\mathbf{curl}(\phi) = \left(\frac{\partial \phi}{\partial x_1}, -\frac{\partial \phi}{\partial x_0} \right)$	curl of a scalar field, when $d = 2$
curl(u)	$\mathbf{curl}(\mathbf{u}) = \frac{\partial u_1}{\partial x_0} - \frac{\partial u_0}{\partial x_1}$	curl of a vector field, when $d = 2$
grad_s(phi)	$\nabla_s \phi = P \nabla \phi$ where $P = I - \mathbf{n} \otimes \mathbf{n}$	tangential gradient of a scalar

Rheolef	mathematics	description
grad_s(u)	$\nabla_s \mathbf{u} = P \nabla \mathbf{u} P$ TODO: $\nabla_s \mathbf{u} = \nabla \mathbf{u} P$	tangential gradient of a vector
Ds(u)	$D_s(\mathbf{u}) = P D(\mathbf{u}) P$	symmetrized tangential gradient
div_s(u)	$\text{div}_s(\mathbf{u}) = \text{tr}(D_s(\mathbf{u}))$	tangential divergence
normal()	\mathbf{n}	unit outward normal on $\Gamma = \partial\Omega$ or on an oriented surface Ω or on an internal oriented side S
jump(phi)	$[[\phi]] = \phi _{K_0} - \phi _{K_1}$	jump accross inter-element side $S = \partial K_0 \cap K_1$
average(phi)	$\{\{\phi\}\} = (\phi _{K_0} + \phi _{K_1})/2$	average accross S
inner(phi)	$\phi _{K_0}$	inner trace on S
outer(phi)	$\phi _{K_1}$	outer trace on S
h_local()	$h_K = \text{meas}(K)^{1/d}$	length scale on an element K
penalty()	$\varpi_s = \max\left(\frac{\text{meas}(\partial K_0)}{\text{meas}(K_0)}, \frac{\text{meas}(\partial K_1)}{\text{meas}(K_1)}\right)$	penalty coefficient on S
grad_h(phi)	$(\nabla_h \phi) _K = \nabla(\phi _K), \forall K \in \mathcal{T}_h$	broken gradient
div_h(u)	$(\text{div}_h \mathbf{u}) _K = \text{div}(\mathbf{u} _K), \forall K \in \mathcal{T}_h$	broken divergence of a vector field
Dh(u)	$(D_h(\mathbf{u})) _K = D(\mathbf{u} _K), \forall K \in \mathcal{T}_h$	broken symmetric part of the gradient of a vector field
sin(phi) cos(phi) tan(phi) acos(phi) asin(phi) atan(phi) cosh(phi) sinh(phi) tanh(phi) exp(phi) log(phi) log10(phi) floor(phi) ceil(phi)	$\sin(\phi)$ $\cos(\phi)$ $\tan(\phi)$ $\cos^{-1}(\phi)$ $\sin^{-1}(\phi)$ $\tan^{-1}(\phi)$ $\cosh(\phi)$ $\sinh(\phi)$ $\tanh(\phi)$ $\exp(\phi)$ $\log(\phi)$ $\log_{10}(\phi)$ $\lfloor \phi \rfloor$ $\lceil \phi \rceil$	standard mathematical functions extended to scalar fields largest integral not greater than ϕ smallest integral not less than ϕ

Rheolef	mathematics	description
<code>min(phi,psi)</code> <code>max(phi,psi)</code> <code>pow(phi,psi)</code> <code>atan2(phi,psi)</code> <code>fmod(phi,psi)</code>	$\min(\phi, \psi)$ $\max(\phi, \psi)$ ϕ^ψ $\tan^{-1}(\psi/\phi)$ $\phi - \lfloor \phi/\psi + 1/2 \rfloor \psi$	floating point remainder
<code>compose(f,phi)</code>	$f(\phi)$	applies an unary function f
<code>compose(f,phi,psi)</code>	$f(\phi, \psi)$	applies a binary function f
<code>compose(phi,X)</code>	$\phi \circ X, X(x) = x + \mathbf{d}(x)$	composition with a characteristic

Part I

Getting started with simple problems

Chapter 1

A scalar first-order problem

The aim of this chapter is to introduce to discontinuous Galerkin methods within the **Rheolef** environment. For some recent presentations of discontinuous Galerkin methods, see [6] for theoretical aspects and [8] for algorithmic and implementation. The discontinuous Galerkin methods are in active development in **Rheolef**, and new features will appear soon.

1.1 The transport equation

The steady scalar transport problem writes:

(P): find ϕ , defined in Ω , such that

$$\begin{aligned}\mathbf{u} \cdot \nabla \phi + \sigma \phi &= f \text{ in } \Omega \\ \phi &= \phi_\Gamma \text{ on } \partial\Omega_-\end{aligned}$$

where \mathbf{u} , $\sigma > 0$, f and ϕ_Γ being known. Notice that this is the steady version of the unsteady diffusion-convection problem previously introduced in section 6.2, page 80 and when the diffusion coefficient ν vanishes. Here, the $\partial\Omega_-$ notation is the *upstream* boundary part, defined by

$$\partial\Omega_- = \{x \in \Omega; \mathbf{u}(x) \cdot \mathbf{n}(x) < 0\}$$

Let us suppose that $\mathbf{u} \in W^{1,\infty}(\Omega)^d$ and introduce the space:

$$X = \{\varphi \in L^2(\Omega); (\mathbf{u} \cdot \nabla)\varphi \in L^2(\Omega)^d\}$$

and, for all $\phi, \varphi \in X$

$$\begin{aligned}a(\phi, \varphi) &= \int_{\Omega} (\mathbf{u} \cdot \nabla \phi \varphi + \sigma \phi \varphi) \, dx + \int_{\partial\Omega} \max(0, -\mathbf{u} \cdot \mathbf{n}) \phi \varphi \, ds \\ l(\varphi) &= \int_{\Omega} f \varphi \, dx + \int_{\partial\Omega} \max(0, -\mathbf{u} \cdot \mathbf{n}) \phi_\Gamma \varphi \, ds\end{aligned}$$

Then, the variational formulation writes:

(FV): find $\phi \in X$ such that

$$a(\phi, \varphi) = l(\varphi), \quad \forall \varphi \in X$$

Notice that the term $\max(0, -\mathbf{u} \cdot \mathbf{n}) = (|\mathbf{u} \cdot \mathbf{n}| - \mathbf{u} \cdot \mathbf{n})/2$ is positive and vanishes everywhere except on $\partial\Omega_-$. Thus, the boundary condition $\phi = \phi_\Gamma$ is weakly imposed on $\partial\Omega_-$ via the integrals on the boundary. The *discontinuous* finite element space is defined by:

$$X_h = \{\varphi_h \in L^2(\Omega); \varphi_h|_K \in P_k, \quad \forall K \in \mathcal{T}_h\}$$

where $k \geq 0$ is the polynomial degree. Notice that $X_h \not\subset X$ and that the $\nabla\phi_h$ term has no more sense for discontinuous functions $\phi_h \in X_h$. Following [6, p. 14], we introduce the *broken gradient* ∇_h as a convenient notation:

$$(\nabla_h \phi_h)|_K = \nabla(\phi_h|_K), \quad \forall K \in \mathcal{T}_h$$

Thus

$$\int_{\Omega} \mathbf{u} \cdot \nabla_h \phi_h \varphi_h \, dx = \sum_{K \in \mathcal{T}_h} \int_K \mathbf{u} \cdot \nabla \phi_h \varphi_h \, dx, \quad \forall \phi_h, \varphi_h \in X_h$$

This leads to a discrete version a_h of the bilinear form a , defined for all $\phi_h, \varphi_h \in X_h$ by (see e.g. [6, p. 57], eqn. (2.34)):

$$\begin{aligned} a_h(\phi_h, \varphi_h) &= \int_{\Omega} (\mathbf{u} \cdot \nabla_h \phi_h \varphi_h + \sigma \phi_h \varphi_h) \, dx + \int_{\partial\Omega} \max(0, -\mathbf{u} \cdot \mathbf{n}) \phi_h \varphi_h \, ds \\ &\quad + \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left(-\mathbf{u} \cdot \mathbf{n} \llbracket \phi_h \rrbracket \{\!\{ \varphi_h \}\!\} + \frac{\alpha}{2} |\mathbf{u} \cdot \mathbf{n}| \llbracket \phi_h \rrbracket \llbracket \varphi_h \rrbracket \right) \, ds \end{aligned}$$

The two last terms involves a sum over $\mathcal{S}_h^{(i)}$, the set of *internal sides* of the mesh \mathcal{T}_h . Each internal side S has two possible orientations: one is chosen definitively. In practice, this orientation is defined in the ‘.geo’ file containing the mesh, where all sides are listed, together with their orientation. Let \mathbf{n} the corresponding normal to the side: as S is an internal side, there exists two elements K_0 and K_1 such that $S = \partial K_0 \cap \partial K_1$ and \mathbf{n} is the outward unit normal of K_0 on $\partial K_0 \cap S$ and the inward unit normal of K_1 on $\partial K_1 \cap S$. We also denote on S the *jump* $\llbracket \phi \rrbracket = \phi|_{K_0} - \phi|_{K_1}$ and the *average* $\{\!\{ \phi \}\!\} = (\phi|_{K_0} + \phi|_{K_1})/2$. The last term in the definition of a_h is ponderated by a coefficient $\alpha \geq 0$. Choosing $\alpha = 0$ correspond to the so-called *centered flux* approximation, while $\alpha = 1$ is the *upwinding flux* approximation. The case $\alpha = 1$ and $k = 0$ (piecewise constant approximation) leads to the popular upwinding finite volume scheme. Finally, the discrete variational formulation writes:

$(FV)_h$: find $\phi_h \in X_h$ such that

$$a_h(\phi_h, \varphi_h) = l(\varphi_h), \quad \forall \varphi_h \in X_h$$

The following code implement this problem in the **Rheolef** environment.

Example file 1.1: `transport_dg.cc`

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 int main(int argc, char**argv) {
5     environment rheolef (argc, argv);
6     geo omega (argv[1]);
7     space Xh (omega, argv[2]);
8     Float alpha = (argc > 3) ? atof(argv[3]) : 1;
9     Float sigma = (argc > 4) ? atof(argv[4]) : 3;
10    point u (1,0,0);
11    trial phi (Xh); test psi (Xh);
12    form ah = integrate (dot(u,grad_h(phi))*psi + sigma*phi*psi)
13              + integrate ("boundary", max(0, -dot(u,normal()))*phi*psi)
14              + integrate ("internal_sides",
15                          - dot(u,normal())*jump(phi)*average(psi)
16                          + 0.5*alpha*abs(dot(u,normal()))*jump(phi)*jump(psi));
17    field lh = integrate ("boundary", max(0, -dot(u,normal()))*psi);
18    solver sah (ah.uu());
19    field phi_h(Xh);
20    phi_h.set_u() = sah.solve(lh.u());
21    dout << catchmark("sigma") << sigma << endl
22          << catchmark("phi") << phi_h;
23 }

```

Comments

The data are $\phi_\gamma = 1$ and $\mathbf{u} = (1, 0, 0)$, and then the exact solution is known: $\phi(x) = \exp(-\sigma x_0)$. The numerical tests are running with $\sigma = 3$ by default. The one-dimensional case writes:

```
make transport_dg
mkgeo_grid -e 10 > line.geo
./transport_dg line P0 | field -
./transport_dg line P1d | field -
./transport_dg line P2d | field -
```

Observe the jumps across elements: these jumps decrease with mesh refinement or when polynomial approximation increases. The two-dimensional case writes:

```
mkgeo_grid -t 10 > square.geo
./transport_dg square P0 | field -elevation -
./transport_dg square P1d | field -elevation -
./transport_dg square P2d | field -elevation -
```

The elevation view shows details on inter-element jumps. Finally, the three-dimensional case writes:

```
mkgeo_grid -T 5 > cube.geo
./transport_dg cube P0 | field -
./transport_dg cube P1d | field -
./transport_dg cube P2d | field -
```

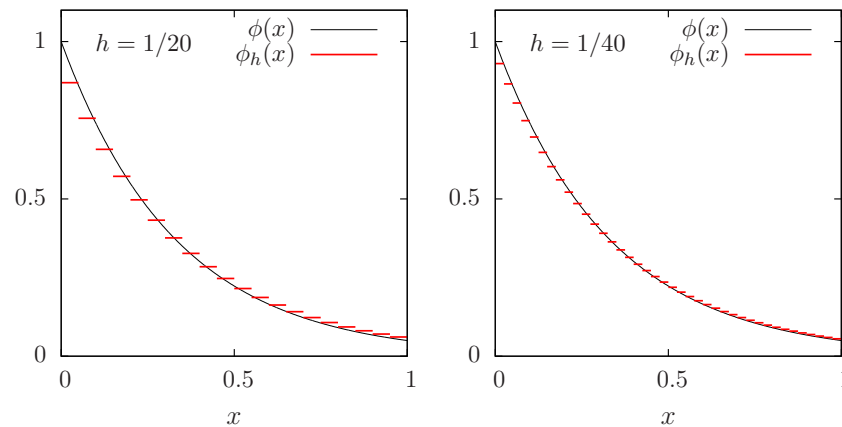


Figure 1.1: The discontinuous Galerkin method for the transport problem when $k = 0$ and $d = 1$.

Fig. 1.1 plots the solution when $d = 1$ and $k = 0$: observe that the boundary condition $\phi = 1$ at $x_0 = 0$ is only weakly satisfied. It means that the approximation $\phi_h(0)$ tends to 1 when h tends to zero. Fig. 1.2 plots the error $\phi - \phi_h$ in L^2 and L^∞ norms: these errors behave as $\mathcal{O}(h^{k+1})$ for all $k \geq 0$, which is optimal. A theoretical $\mathcal{O}(h^{k+1/2})$ error bound was shown in [9]. The present numerical results confirm that these theoretical error bounds can be improved for some families of meshes, as pointed out by Richter [11], that showed a $\mathcal{O}(h^{k+1})$ optimal bound for the transport problem. This result was recently extended by Cockburn *et al.* [2], while Peterson [10] showed that the estimate $\mathcal{O}(h^{k+1/2})$ is sharp for general families of quasi-uniform meshes.

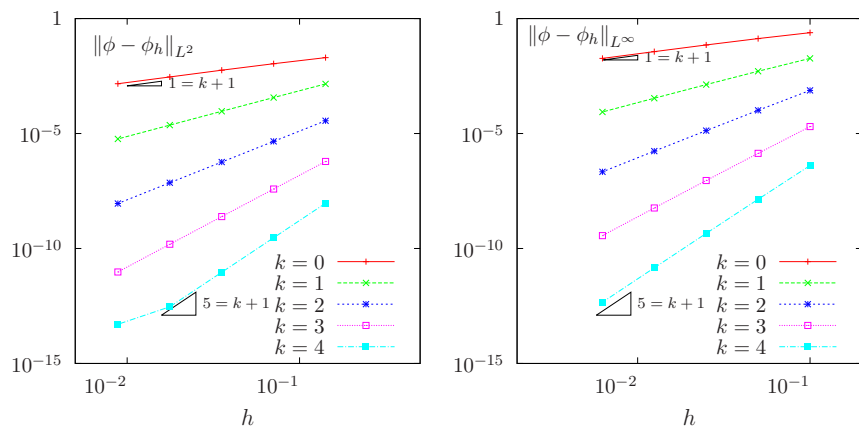


Figure 1.2: The discontinuous Galerkin method for the transport problem: convergence when $d = 2$.

Chapter 2

Scalar second-order problems

2.1 The Poisson problem with Dirichlet boundary conditions

The Poisson problem with non-homogeneous Dirichlet boundary conditions has been already introduced in volume 1, section 2.1, page 23:

(P): find u , defined in Ω , such that

$$\begin{aligned} -\Delta u &= f \text{ in } \Omega \\ u &= g \text{ on } \partial\Omega \end{aligned}$$

where f and g are given.

The *discontinuous* finite element space is defined by:

$$X_h = \{v_h \in L^2(\Omega); v_h|_K \in P_k, \forall K \in \mathcal{T}_h\}$$

where $k \geq 1$ is the polynomial degree. As elements of X_h do not belong to $H^1(\Omega)$, due to discontinuities at inter-elements, we introduce the broken Sobolev space:

$$H^1(\mathcal{T}_h) = \{v \in L^2(\Omega); v|_K \in H^1(K), \forall K \in \mathcal{T}_h\}$$

such that $X_h \subset H^1(\mathcal{T}_h)$. We introduce the following bilinear form $a_h(\cdot, \cdot)$ and linear form $l_h(\cdot)$, defined for all $u, v \in H^1(\mathcal{T}_h)$ by (see e.g. [6, p. 125 and 127], eqn. (4.12)):

$$a_h(u, v) = \int_{\Omega} \nabla_h u \cdot \nabla_h v \, dx + \sum_{S \in \mathcal{S}_h} \int_S (\eta_s \llbracket u \rrbracket \llbracket v \rrbracket - \{\!\!\{ \nabla_h u \cdot \mathbf{n} \}\!\!\} \llbracket v \rrbracket - \llbracket u \rrbracket \{\!\!\{ \nabla_h v \cdot \mathbf{n} \}\!\!\}) \, ds \quad (2.1)$$

$$l_h(v) = \int_{\Omega} f u \, dx + \int_{\partial\Omega} (\eta_s g v - g \nabla_h v \cdot \mathbf{n}) \, ds \quad (2.2)$$

The last term involves a sum over \mathcal{S}_h , the set of *all sides* of the mesh \mathcal{T}_h , i.e. the internal sides and the boundary sides. By convenience, the definition of the jump and average are extended to all boundary sides as $\llbracket u \rrbracket = \{\!\!\{ u \}\!\!\} = u$. Notice that, as for the previous transport problem, the Dirichlet boundary condition $u = g$ is weakly imposed on $\partial\Omega$ via the integrals on the boundary. Finally, $\eta_s > 0$ is a stabilization parameter on a side S . The stabilization term associated to η_s is present in order to achieve coercivity: it penalize interface and boundary jumps. A common choice is $\eta_s = \beta h_s^{-1}$ where $\beta > 0$ is a constant and h_s is a local length scale associated to the current side S . One drawback to this choice is that it requires the end user to specify the numerical constant β . From one hand, if the value of this parameter is not sufficiently large, the form $a_h(\cdot, \cdot)$ is not coercive and the approximate solution develops instabilities and do not converge [7]. From other hand, if the value of this parameter is too large, it affects the overall efficiency of the iterative solver of the linear system: the spectral condition number of the matrix associated to $a_h(\cdot, \cdot)$

grows linearly with this parameter [1]. An explicit choice of penalty parameter is proposed in [12]: $\eta_s = \beta \varpi_s$ where $\beta = (k+1)(k+d)/d$ and

$$\varpi_s = \begin{cases} \frac{\text{meas}(\partial K)}{\text{meas}(K)} & \text{when } S = K \cap \partial\Omega \text{ is a boundary side} \\ \max\left(\frac{\text{meas}(\partial K_0)}{\text{meas}(K_0)}, \frac{\text{meas}(\partial K_1)}{\text{meas}(K_1)}\right) & \text{when } S = K_0 \cap K_1 \text{ is an internal side} \end{cases}$$

Notice that ϖ_s scales as h_s^{-1} . Now, the computation of the penalty parameter is fully automatic and the convergence of the method is always guaranteed to converge. Moreover, this choice has been founded to be sharp and it preserves the optimal efficiency of the iterative solvers. Finally, the discrete variational formulation writes:

$(FV)_h$: find $u_h \in X_h$ such that

$$a_h(u_h, v_h) = l_h(v_h), \forall v_h \in X_h$$

The following code implement this problem in the **Rheolef** environment.

Example file 2.1: dirichlet_dg.cc

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 #include "cosinusprod_laplace.icc"
5 int main(int argc, char**argv) {
6     environment rheolef (argc, argv);
7     geo omega (argv[1]);
8     space Xh (omega, argv[2]);
9     size_t d = omega.dimension();
10    size_t k = Xh.degree();
11    Float beta = (k+1)*(k+d)/d;
12    trial u (Xh); test v (Xh);
13    form a = integrate (dot(grad_h(u), grad_h(v)))
14            + integrate ("sides", beta*penalty()*jump(u)*jump(v)
15                        - jump(u)*average(dot(grad_h(v), normal()))
16                        - jump(v)*average(dot(grad_h(u), normal())));
17    field lh = integrate (f(d)*v)
18                + integrate ("boundary", beta*penalty()*g(d)*v
19                            - g(d)*dot(grad_h(v), normal()));
20    solver sa (a.uu());
21    field uh(Xh);
22    uh.set_u() = sa.solve(lh.u());
23    dout << uh;
24 }

```

Comments

The `penalty()` pseudo-function implements the computation of ϖ_s in **Rheolef**. The right-hand side f and g are given by (2.1), volume 1, page 24. In that case, the exact solution is known. Running the one-dimensional case writes:

```

make dirichlet_dg
mkgeo_grid -e 10 > line.geo
./dirichlet_dg line P1d | field -
./dirichlet_dg line P2d | field -

```

Fig. 2.1 plots the one-dimensional solution when $k = 1$ for two meshes. Observe that the jumps at inter-element nodes decreases very fast with mesh refinement and are no more perceptible on the plots. Recall that the Dirichlet boundary conditions at $x = 0$ and $x = 1$ is only weakly imposed: the corresponding jump at the boundary is also not perceptible.

The two-dimensional case writes:

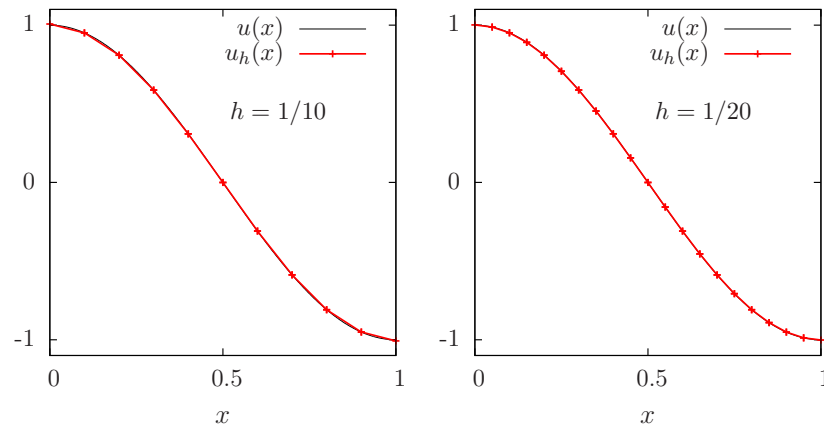


Figure 2.1: The discontinuous Galerkin method for the Poisson problem when $k = 1$ and $d = 1$.

```
mkgeo_grid -t 10 > square.geo
./dirichlet_dg square P1d | field -elevation -
./dirichlet_dg square P2d | field -elevation -
```

and the three-dimensional one

```
mkgeo_grid -T 10 > cube.geo
./dirichlet_dg cube P1d | field -elevation -
./dirichlet_dg cube P2d | field -elevation -
```

Error analysis

The space $H^1(\mathcal{T}_h)$ is equipped with the norm $\|\cdot\|_{1,h}$, defined for all $v \in H^1(\mathcal{T}_h)$ by [6, p. 128]:

$$\|v\|_{1,h}^2 = \|\nabla_h v\|_{0,\Omega}^2 + \sum_{S \in \mathcal{S}_h} \int_S h_s^{-1} [v]^2 ds$$

The code `cosinusprod_error_dg.cc` compute the error in these norms. This code it is not listed here but is available in the **Rheolef** example directory. The computation of the error writes:

```
make cosinusprod_error_dg
./dirichlet_dg square P1d | cosinusprod_error_dg
```

Fig. 2.2 plots the error $u - u_h$ in L^2 , L^∞ and the $\|\cdot\|_{1,h}$ norms. The L^2 and L^∞ error norms behave as $\mathcal{O}(h^{k+1})$ for all $k \geq 0$, while the $\|\cdot\|_{1,h}$ one behaves as $\mathcal{O}(h^k)$, which is optimal.

2.2 The Helmholtz problem with Neumann boundary conditions

The Poisson problem with non-homogeneous Neumann boundary conditions has been already introduced in volume 1, section 2.2, page 31:

(P): find u , defined in Ω , such that

$$\begin{aligned} u - \Delta u &= f \text{ in } \Omega \\ \frac{\partial u}{\partial n} &= g \text{ on } \partial\Omega \end{aligned}$$

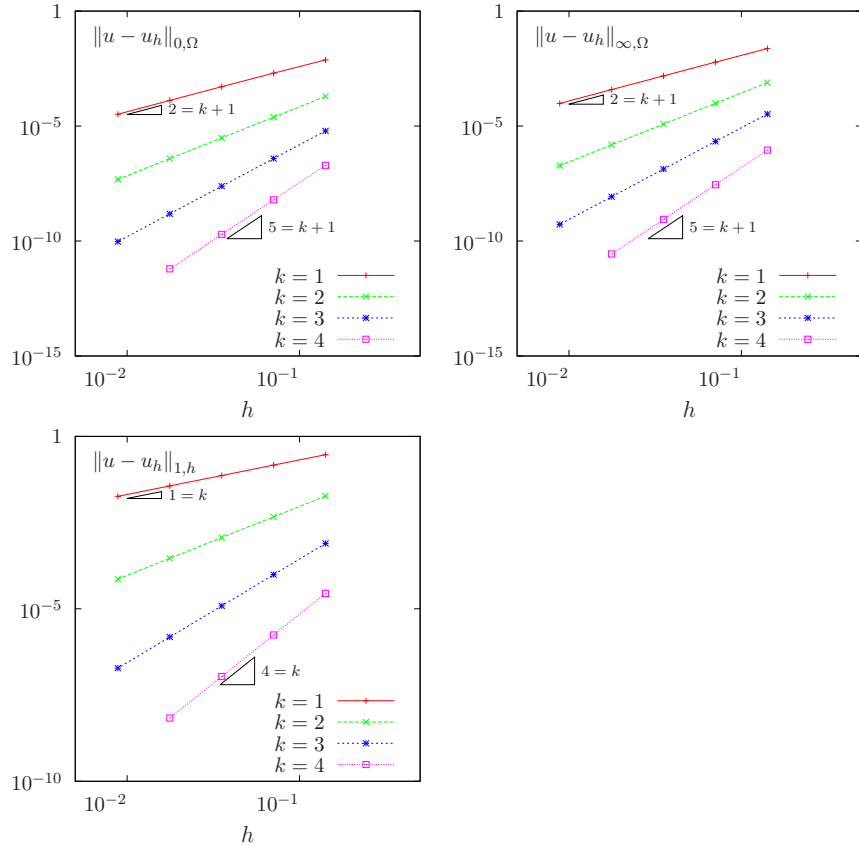


Figure 2.2: The discontinuous Galerkin method for the Poisson problem: convergence when $d = 2$.

where f and g are given. We introduce the following bilinear form $a_h(\cdot, \cdot)$ and linear form $l_h(\cdot)$, defined for all $u, v \in H^1(\mathcal{T}_h)$ by (see e.g. [6, p. 127], eqn. (4.16)):

$$a_h(u, v) = \int_{\Omega} (uv + \nabla_h u \cdot \nabla_h v) \, dx \quad (2.3)$$

$$+ \sum_{S \in \mathcal{S}_h^{(i)}} \int_S (\beta \varpi_s \llbracket u \rrbracket \llbracket v \rrbracket - \{\{ \nabla_h u \cdot \mathbf{n} \} \} \llbracket v \rrbracket - \llbracket u \rrbracket \{\{ \nabla_h v \cdot \mathbf{n} \} \}) \, ds \quad (2.4)$$

$$l_h(v) = \int_{\Omega} f u \, dx + \int_{\partial\Omega} g v \, ds \quad (2.5)$$

Let us comment the changes between these forms and those used for the Poisson problem with Dirichlet boundary conditions. The Poisson operator $-\Delta$ has been replaced by the Helmholtz one $I - \Delta$ in order to have an unique solution. Remark also that the sum is performed in (2.1) for all internal sides in $\mathcal{S}_h^{(i)}$, while, in (2.1), for Dirichlet boundary conditions, it was for all sides in \mathcal{S}_h , i.e. for both boundary and internal sides. Also, the right-hand-side linear form $l_h(\cdot)$ do no more involves any sum over sides.

Finally, the discrete variational formulation writes:

$(FV)_h$: find $u_h \in X_h$ such that

$$a_h(u_h, v_h) = l_h(v_h), \quad \forall v_h \in X_h$$

The following code implement this problem in the **Rheolef** environment.

Example file 2.2: neumann_dg.cc

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 #include "sinusprod_helmholtz.icc"
5 int main(int argc, char**argv) {
6     environment rheolef (argc, argv);
7     geo omega (argv[1]);
8     space Xh (omega, argv[2]);
9     size_t d = omega.dimension();
10    size_t k = Xh.degree();
11    Float beta = (k+1)*(k+d)/d;
12    trial u (Xh); test v (Xh);
13    form a = integrate (u*v + dot(grad_h(u),grad_h(v)))
14            + integrate ("internal_sides",
15                        beta*penalty()*jump(u)*jump(v)
16                        - jump(u)*average(dot(grad_h(v),normal()))
17                        - jump(v)*average(dot(grad_h(u),normal())));
18    field lh = integrate (f(d)*v) + integrate ("boundary", g(d)*v);
19    solver sa (a.uu());
20    field uh(Xh);
21    uh.set_u() = sa.solve(lh.u());
22    dout << uh;
23 }

```

Comments

The right-hand side f and g are given by (2.2), volume 1, page 24. In that case, the exact solution is known. Running the program is obtained from the non-homogeneous Dirichlet case, by replacing `dirichlet_dg` by `neumann_dg`.

Part II

Fluids and solids computations

Chapter 3

The linear elasticity and the Stokes problems

3.1 The linear elasticity problem

The elasticity problem (4.2) has been introduced in volume 1, section 4.1, page 47.

(P): find \mathbf{u} such that

$$\begin{aligned} -\operatorname{div}(\lambda \operatorname{div}(\mathbf{u}).I + 2D(\mathbf{u})) &= \mathbf{f} \text{ in } \Omega \\ \mathbf{u} &= \mathbf{g} \text{ on } \partial\Omega \end{aligned}$$

where $\lambda \geq -1$ is a constant and \mathbf{f}, \mathbf{g} given. This problem is a natural extension to vector-valued field of the Poisson problem with Dirichlet boundary conditions.

The variational formulation writes:

(FV)_h: find $\mathbf{u} \in \mathbf{V}(\mathbf{g})$ such that

$$a(\mathbf{u}, \mathbf{v}) = l_h(\mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{V}(0)$$

where

$$\begin{aligned} \mathbf{V}(\mathbf{g}) &= \{\mathbf{v} \in H^1(\Omega)^d; \mathbf{v} = \mathbf{g} \text{ on } \partial\Omega\} \\ a(\mathbf{u}, \mathbf{v}) &= \int_{\Omega} (\lambda \operatorname{div}(\mathbf{u}) \operatorname{div}(\mathbf{v}) + 2D(\mathbf{u}) : D(\mathbf{v})) \, dx \\ l_h(\mathbf{v}) &= \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, dx \end{aligned}$$

The discrete variational formulation writes:

(FV)_h: find $u_h \in \mathbf{X}_h$ such that

$$a_h(u_h, v_h) = l_h(v_h), \quad \forall v_h \in \mathbf{X}_h$$

where

$$\begin{aligned} \mathbf{X}_h &= \{\mathbf{v}_h \in L^2(\Omega)^d; \mathbf{v}_h|_K \in P_k^d, \forall K \in \mathcal{T}_h\} \\ a_h(\mathbf{u}, \mathbf{v}) &= \int_{\Omega} (\lambda \operatorname{div}_h(\mathbf{u}) \operatorname{div}_h(\mathbf{v}) + 2D_h(\mathbf{u}) : D_h(\mathbf{v})) \, dx \\ &\quad + \sum_{S \in \mathcal{S}_h} \int_S (\beta \varpi_s \llbracket \mathbf{u} \rrbracket \cdot \llbracket \mathbf{v} \rrbracket - \llbracket \mathbf{u} \rrbracket \cdot \{\{\lambda \operatorname{div}_h(\mathbf{v})\mathbf{n} + 2D_h(\mathbf{v})\mathbf{n}\}\} - \llbracket \mathbf{v} \rrbracket \cdot \{\{\lambda \operatorname{div}_h(\mathbf{u})\mathbf{n} + 2D_h(\mathbf{u})\mathbf{n}\}\}) \, ds \\ l_h(\mathbf{v}) &= \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, dx + \int_{\partial\Omega} \mathbf{g} \cdot (\beta \varpi_s \mathbf{v} - \lambda \operatorname{div}_h(\mathbf{v})\mathbf{n} - 2D_h(\mathbf{v})\mathbf{n}) \, ds \end{aligned}$$

where $k \geq 1$ is the polynomial degree in \mathbf{X}_h .

Example file 3.1: elasticity_taylor_dg.cc

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 #include "taylor.icc"
5 int main(int argc, char**argv) {
6     environment rheolef (argc, argv);
7     geo omega (argv[1]);
8     space Xh (omega, argv[2], "vector");
9     Float lambda = (argc > 3) ? atof(argv[3]) : 1;
10    size_t d = omega.dimension();
11    size_t k = Xh.degree();
12    Float beta = (k+1)*(k+d)/d;
13    trial u (Xh); test v (Xh);
14    form a = integrate (lambda*div_h(u)*div_h(v) + 2*ddot(Dh(u),Dh(v)))
15            + integrate (omega.sides(),
16                        beta*penalty()*dot(jump(u),jump(v))
17                        - lambda*dot(jump(u),average(div_h(v)*normal()))
18                        - lambda*dot(jump(v),average(div_h(u)*normal()))
19                        - 2*dot(jump(u),average(Dh(v)*normal()))
20                        - 2*dot(jump(v),average(Dh(u)*normal())));
21    field lh = integrate (dot(f(),v))
22                + integrate (omega.boundary(),
23                            beta*penalty()*dot(g(),jump(v))
24                            - lambda*dot(g(),average(div_h(v)*normal()))
25                            - 2*dot(g(),average(Dh(v)*normal())));
26    solver sa (a.uu());
27    field uh(Xh);
28    uh.set_u() = sa.solve(lh.u());
29    dout << uh;
30 }

```

Comments

The data are given when $d = 2$ by:

$$\mathbf{g}(x) = \begin{pmatrix} -\cos(\pi x_0) \sin(\pi x_1) \\ \sin(\pi x_0) \cos(\pi x_1) \end{pmatrix} \quad \text{and} \quad \mathbf{f} = 2\pi^2 \mathbf{g} \quad (3.1)$$

This choice is convenient since the exact solution is known $\mathbf{u} = \mathbf{g}$. This benchmark solution was proposed in 1923 by Taylor [13] in the context of the Stokes problem. Notice that the solution is independent of λ since $\text{div}(\mathbf{u}) = 0$.

Example file 3.2: taylor.icc

```

1 struct g: field_function<g,point> {
2     point operator() (const point& x) const {
3         return point(-cos(pi*x[0])*sin(pi*x[1]),
4                     sin(pi*x[0])*cos(pi*x[1])); }
5     g() : pi(acos(Float(-1.0))) {}
6     const Float pi;
7 };
8 struct f: field_function<f,point> {
9     point operator() (const point& x) const { return 2*sqr(pi)*_g(x); }
10    f() : pi(acos(Float(-1.0))), _g() {}
11    const Float pi; g _g;
12 };

```

As the exact solution is known, the error can be computed. The code code `elasticity_taylor_error_dg.cc` compute the error in L^2 , L^∞ and energy norms. This code it is not listed here but is available in the **Rheolef** example directory. The computation writes:

```
make elasticity_taylor_dg elasticity_taylor_error_dg
```

```
mkgeo_grid -t 10 > square.geo
./elasticity_taylor_dg square P1d | ./elasticity_taylor_error_dg
./elasticity_taylor_dg square P2d | ./elasticity_taylor_error_dg
```

3.2 The Stokes problem

Let us consider the Stokes problem for the driven cavity in $\Omega =]0, 1[^d$, $d = 2, 3$. The problem has been introduced in volume 1, section 4.4, page 57.

(P): find \mathbf{u} and p , defined in Ω , such that

$$\begin{aligned} -\operatorname{div}(2D(\mathbf{u})) + \nabla p &= \mathbf{f} \text{ in } \Omega, \\ -\operatorname{div} \mathbf{u} &= 0 \text{ in } \Omega, \\ \mathbf{u} &= \mathbf{g} \text{ on } \partial\Omega \end{aligned}$$

where \mathbf{f} and \mathbf{g} are given. This problem is the extension to divergence free vector fields of the elasticity problem. The variational formulation writes:

$(VF)_h$ find $\mathbf{u} \in \mathbf{V}(\mathbf{g})$ and $p \in L^2(\Omega)$ such that:

$$\begin{aligned} a(\mathbf{u}, \mathbf{v}) + b(\mathbf{v}, p) &= l(\mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{V}(0), \\ b(\mathbf{u}, q) &= 0, \quad \forall q \in L^2(\Omega) \end{aligned} \quad (3.2)$$

where

$$\begin{aligned} \mathbf{V}(\mathbf{g}) &= \{\mathbf{v} \in H^1(\Omega)^d; \mathbf{v} = \mathbf{g} \text{ on } \partial\Omega\} \\ a(\mathbf{u}, \mathbf{v}) &= \int_{\Omega} 2D(\mathbf{u}) : D(\mathbf{v}) \, dx \\ b(\mathbf{u}, q) &= - \int_{\Omega} \operatorname{div}(\mathbf{u}) \, q \, dx \\ l(\mathbf{v}) &= \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, dx \end{aligned}$$

The discrete variational formulation writes:

$(VF)_h$ find $\mathbf{u}_h \in \mathbf{X}_h$ and $p_h \in Q_h$ such that:

$$\begin{aligned} a_h(\mathbf{u}_h, \mathbf{v}_h) + b_h(\mathbf{v}_h, p_h) &= l_h(\mathbf{v}_h), \quad \forall \mathbf{v}_h \in \mathbf{X}_h, \\ b_h(\mathbf{u}_h, q_h) - c_h(p_h, q_h) &= k_h(q), \quad \forall q_h \in Q_h. \end{aligned} \quad (3.3)$$

The discontinuous finite element spaces are defined by:

$$\begin{aligned} \mathbf{X}_h &= \{\mathbf{v}_h \in L^2(\Omega)^d; \mathbf{v}_h|_K \in P_k^d, \forall K \in \mathcal{T}_h\} \\ Q_h &= \{q_h \in L^2(\Omega)^d; q_h|_K \in P_k^d, \forall K \in \mathcal{T}_h\} \end{aligned}$$

where $k \geq 1$ is the polynomial degree. Notice that velocity and pressure are approximated by the same polynomial order. This method was introduced by [4] and some recent theoretical results can be founded in [5]. The forms are defined for all $u, v \in H^1(\mathcal{T}_h)^d$ and $q \in L^2(\Omega)$ by (see

e.g. [6, p. 249]):

$$\begin{aligned}
 a_h(\mathbf{u}, \mathbf{v}) &= \int_{\Omega} 2D_h(\mathbf{u}) : D_h(\mathbf{v}) \, dx \\
 &\quad + \sum_{S \in \mathcal{S}_h} \int_S (\beta \varpi_s [\mathbf{u}] \cdot [\mathbf{v}] - [\mathbf{u}] \cdot \{2D_h(\mathbf{v})\mathbf{n}\} - [\mathbf{v}] \cdot \{2D_h(\mathbf{u})\mathbf{n}\}) \, ds \\
 b_h(\mathbf{u}, q) &= \int_{\Omega} \mathbf{u} \cdot \nabla_h q \, dx - \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \{ \mathbf{u} \} \cdot \mathbf{n} [q] \, ds \\
 c_h(p, q) &= \sum_{S \in \mathcal{S}_h^{(i)}} \int_S h_s [p] [q] \, ds \\
 l_h(\mathbf{v}) &= \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, dx + \int_{\partial\Omega} \mathbf{g} \cdot (\beta \varpi_s \mathbf{v} - 2D_h(\mathbf{v})\mathbf{n}) \, ds \\
 k_h(q) &= \int_{\partial\Omega} \mathbf{g} \cdot \mathbf{n} q \, ds
 \end{aligned}$$

The stabilization form c_h controls the pressure jump across internal sides. This stabilization term is necessary when using equal order polynomial approximation for velocity and pressure. The definition of the forms is grouped in a subroutine: it will be reused later for the Navier-Stokes problem.

Example file 3.3: stokes_dirichlet_dg.icc

```

1 void stokes_dirichlet_dg (const space& Xh, const space& Qh,
2   form& a, form& b, form& c, form& mp, field& lh, field& kh,
3   quadrature_option_type qopt = quadrature_option_type())
4 {
5   size_t k = Xh.degree();
6   size_t d = Xh.get_geo().dimension();
7   Float beta = (k+1)*(k+d)/d;
8   trial u (Xh), p (Qh);
9   test v (Xh), q (Qh);
10  a = integrate (2*ddot(Dh(u),Dh(v)), qopt)
11    + integrate ("sides", beta*penalty()*dot(jump(u), jump(v))
12      - 2*dot(jump(u), average(Dh(v)*normal()))
13      - 2*dot(jump(v), average(Dh(u)*normal())), qopt);
14  lh = integrate (dot(f(),v), qopt)
15    + integrate ("boundary", beta*penalty()*dot(g(),v)
16      - 2*dot(g(),Dh(v)*normal()), qopt);
17  b = integrate (dot(u,grad_h(q)), qopt)
18    + integrate ("internal_sides", - dot(average(u), normal())*jump(q), qopt);
19  kh = integrate ("boundary", dot(g(),normal())*q, qopt);
20  c = integrate ("internal_sides", h_local()*jump(p)*jump(q), qopt);
21  mp = integrate (p*q, qopt);
22 }

```

A simple test program writes:

Example file 3.4: stokes_taylor_dg.cc

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 #include "taylor.icc"
5 #include "stokes_dirichlet_dg.icc"
6 int main(int argc, char**argv) {
7     environment rheolef (argc, argv);
8     geo omega (argv[1]);
9     space Xh (omega, argv[2], "vector");
10    space Qh (omega, argv[2]);
11    form a, b, c, mp;
12    field lh, kh;
13    stokes_dirichlet_dg (Xh, Qh, a, b, c, mp, lh, kh);
14    field uh (Xh, 0), ph (Qh, 0);
15    solver_abtb stokes (a.uu(), b.uu(), c.uu(), mp.uu());
16    stokes.solve (lh.u(), kh.u(), uh.set_u(), ph.set_u());
17    dout << catchmark("u") << uh
18         << catchmark("p") << ph;
19 }

```

Comments

The data are given when $d = 2$ by (3.1). This choice is convenient since the exact solution is known $\mathbf{u} = \mathbf{g}$ and $p = 0$. The code `stokes_taylor_error_dg.cc` compute the error in L^2 , L^∞ and energy norms. This code it is not listed here but is available in the **Rheolef** example directory. The computation writes:

```

make stokes_taylor_dg stokes_taylor_error_dg
mkgeo_grid -t 10 > square.geo
./stokes_taylor_dg square P1d | ./stokes_taylor_error_dg
./stokes_taylor_dg square P2d | ./stokes_taylor_error_dg

```

3.3 The stationary Navier-Stokes problem

3.3.1 Problem statement

The Navier-Stokes problem has been already introduced in volume 1, section 3.3 page 23. Here we consider the stationary version of this problem. Let $Re \geq 0$ be the Reynolds number. The problem writes:

(P): find \mathbf{u} and p , defined in Ω , such that

$$\begin{aligned}
 Re(\mathbf{u} \cdot \nabla) \mathbf{u} - \operatorname{div}(2D(\mathbf{u})) + \nabla p &= \mathbf{f} \text{ in } \Omega, \\
 -\operatorname{div} \mathbf{u} &= 0 \text{ in } \Omega, \\
 \mathbf{u} &= \mathbf{g} \text{ on } \partial\Omega
 \end{aligned}$$

Notice that, when $Re > 0$, the problem is nonlinear, due to the inertia term $\mathbf{u} \cdot \nabla \mathbf{u}$. When $Re = 0$ the problem reduces to the linear Stokes problem, presented in the previous section/

The variational formulation of this nonlinear problem writes:

(FV): find $\mathbf{u} \in \mathbf{V}(\mathbf{g})$ and $p \in L^2(\Omega)$ such that

$$\begin{aligned}
 Ret(\mathbf{u}; \mathbf{u}, \mathbf{v}) + a(\mathbf{u}, \mathbf{v}) + b(\mathbf{v}, p) &= l(\mathbf{v}), \forall \mathbf{v} \in \mathbf{V}(0), \\
 b(\mathbf{u}, q) &= 0, \forall q \in L^2(\Omega)
 \end{aligned}$$

where the space $\mathbf{V}(\mathbf{g})$ and forms a , b and l are given as in the previous section 3.2 for the Stokes problem and the trilinear form $t(\cdot; \cdot, \cdot)$ is given by:

$$t(\mathbf{w}; \mathbf{u}, \mathbf{v}) = \int_{\Omega} ((\mathbf{w} \cdot \nabla) \mathbf{u}) \cdot \mathbf{v} \, dx$$

3.3.2 The discrete problem

Let

$$t(\mathbf{w}; \mathbf{u}, \mathbf{u}) = \int_{\Omega} (\mathbf{w} \cdot \nabla \mathbf{u}) \cdot \mathbf{u} \, dx$$

Observe that, for all $\mathbf{u}, \mathbf{w} \in H^1(\Omega)^d$ we have

$$\begin{aligned} \int_{\Omega} (\mathbf{w} \cdot \nabla \mathbf{u}) \cdot \mathbf{u} \, dx &= \sum_{i,j=0}^{d-1} \int_{\Omega} u_i w_j \partial_j(u_i) \, dx \\ &= \sum_{i,j=0}^{d-1} - \int_{\Omega} u_i \partial_j(u_i w_j) \, dx + \int_{\partial\Omega} u_i^2 w_j n_j \, dx \\ &= \sum_{i,j=0}^{d-1} - \int_{\Omega} u_i \partial_j(u_i) w_j \, dx - \int_{\Omega} u_i^2 \partial_j(w_j) \, dx + \int_{\partial\Omega} u_i^2 w_j n_j \, dx \\ &= - \int_{\Omega} (\mathbf{w} \cdot \nabla \mathbf{u}) \cdot \mathbf{u} \, dx - \int_{\Omega} \operatorname{div}(\mathbf{w}) |\mathbf{u}|^2 \, dx + \int_{\partial\Omega} \mathbf{w} \cdot \mathbf{n} |\mathbf{u}|^2 \, ds \end{aligned} \quad (3.4)$$

Thus

$$t(\mathbf{w}; \mathbf{u}, \mathbf{u}) = \int_{\Omega} (\mathbf{w} \cdot \nabla \mathbf{u}) \cdot \mathbf{u} \, dx = -\frac{1}{2} \int_{\Omega} \operatorname{div}(\mathbf{w}) |\mathbf{u}|^2 \, dx + \frac{1}{2} \int_{\partial\Omega} \mathbf{w} \cdot \mathbf{n} |\mathbf{u}|^2 \, ds$$

When $\operatorname{div}(\mathbf{w}) = 0$, the trilinear form $t(\cdot, \cdot, \cdot)$ reduces to a boundary term: it is formally skew-symmetric. The skew-symmetry of t is an important property: let $(\mathbf{v}, q) = (\mathbf{u}, p)$ as test functions in (FV) . We obtain:

$$a(\mathbf{u}, \mathbf{u}) = l(\mathbf{u})$$

In other words, we obtain the same energy balance as for the Stokes flow and inertia do not contribute to the energy balance. This is an important property and we aim at obtaining the same one at the discrete level. As the discrete solution \mathbf{u}_h is not exactly divergence free, following Temam, we introduce the following modified trilinear form:

$$t^*(\mathbf{w}; \mathbf{u}, \mathbf{v}) = \int_{\Omega} \left((\mathbf{w} \cdot \nabla \mathbf{u}) \cdot \mathbf{v} + \frac{1}{2} \operatorname{div}(\mathbf{w}) \mathbf{u} \cdot \mathbf{v} \right) dx - \frac{1}{2} \int_{\partial\Omega} (\mathbf{w} \cdot \mathbf{n}) \mathbf{u} \cdot \mathbf{v} \, ds, \quad \forall \mathbf{u}, \mathbf{v}, \mathbf{w} \in H^1(\Omega)^d$$

This form integrates the non-vanishing terms and we have:

$$t^*(\mathbf{w}; \mathbf{u}, \mathbf{u}) = 0, \quad \forall \mathbf{u}, \mathbf{w} \in H^1(\Omega)^d$$

When the discrete solution is not exactly divergence free, it is better to use t^* than t .

The discontinuous finite element spaces \mathbf{X}_h and Q_h and forms a_h, b_h, c_h, l_h and k_h are defined as in the previous section. Let us introduce t_h^* , the following discrete trilinear form, defined for all $\mathbf{u}_h, \mathbf{v}_h, \mathbf{w}_h \in \mathbf{X}_h$:

$$t_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) = \int_{\Omega} \left((\mathbf{w}_h \cdot \nabla_h \mathbf{u}_h) \cdot \mathbf{v}_h + \frac{1}{2} \operatorname{div}_h(\mathbf{w}_h) \mathbf{u}_h \cdot \mathbf{v}_h \right) dx - \frac{1}{2} \int_{\partial\Omega} (\mathbf{w}_h \cdot \mathbf{n}) \mathbf{u}_h \cdot \mathbf{v}_h \, ds$$

Notice that t_h^* is similar to t^* : the gradient and divergence has been replaced by their broken counterpart in the first term. As $\mathbf{X}_h \not\subset H^1(\Omega)^d$, the skew-symmetry property is not expected to be true at the discrete level. Then

$$t_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{u}_h) = \sum_{K \in \mathcal{T}_h} \int_K \left((\mathbf{w}_h \cdot \nabla \mathbf{u}_h) \cdot \mathbf{u}_h + \frac{1}{2} \operatorname{div}(\mathbf{w}_h) |\mathbf{u}_h|^2 \right) dx - \frac{1}{2} \int_{\partial\Omega} (\mathbf{w}_h \cdot \mathbf{n}) |\mathbf{u}_h|^2 \, ds$$

As the restriction of \mathbf{u}_h and \mathbf{w}_h to each $K \in \mathcal{T}_h$ belongs to $H^1(K)^d$, we have, using a similar integration by part:

$$\int_K (\mathbf{w}_h \cdot \nabla \mathbf{u}_h) \cdot \mathbf{u}_h \, dx = -\frac{1}{2} \int_K \operatorname{div}(\mathbf{w}_h) |\mathbf{u}_h|^2 \, dx + \frac{1}{2} \int_{\partial K} (\mathbf{w}_h \cdot \mathbf{n}) |\mathbf{u}_h|^2 \, ds$$

Thus

$$t_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{u}_h) = \frac{1}{2} \sum_{K \in \mathcal{T}_h} \int_{\partial K} (\mathbf{w}_h \cdot \mathbf{n}) |\mathbf{u}_h|^2 \, ds - \frac{1}{2} \int_{\partial \Omega} (\mathbf{w}_h \cdot \mathbf{n}) |\mathbf{u}_h|^2 \, ds$$

The terms on boundary sides vanish while those on internal sides can be grouped:

$$t_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{u}_h) = \frac{1}{2} \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \llbracket |\mathbf{u}_h|^2 \mathbf{w}_h \rrbracket \cdot \mathbf{n} \, ds$$

The jump term $\llbracket (\mathbf{u}_h \cdot \mathbf{v}_h) \mathbf{w}_h \rrbracket \cdot \mathbf{n}$ is not easily manageable and could be developed. A short computation shows that, for all scalar fields ϕ, φ we have on any internal side:

$$\llbracket \phi \varphi \rrbracket = \llbracket \phi \rrbracket \{\varphi\} + \{\phi\} \llbracket \varphi \rrbracket \quad (3.5)$$

$$\{\phi \varphi\} = \{\phi\} \{\varphi\} + \frac{1}{4} \llbracket \phi \rrbracket \llbracket \varphi \rrbracket \quad (3.6)$$

Then

$$\begin{aligned} t_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{u}_h) &= \frac{1}{2} \sum_{S \in \mathcal{S}_h^{(i)}} \int_S (\{\mathbf{w}_h\} \cdot \mathbf{n} \llbracket |\mathbf{u}_h|^2 \rrbracket + \llbracket \mathbf{w}_h \rrbracket \cdot \mathbf{n} \{\!|\mathbf{u}_h|^2\!\}) \, ds \\ &= \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left(\{\mathbf{w}_h\} \cdot \mathbf{n} (\llbracket \mathbf{u}_h \rrbracket \cdot \{\!|\mathbf{u}_h|^2\!\}) + \frac{1}{2} \llbracket \mathbf{w}_h \rrbracket \cdot \mathbf{n} \{\!|\mathbf{u}_h|^2\!\} \right) \, ds \end{aligned}$$

Thus, as expected, the skew-symmetry property is no more satisfied at the discrete level, due to the jumps of the fields at the inter-element boundaries. Following the previous idea, we introduce the following modified discrete trilinear form:

$$\begin{aligned} t_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) &= t_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) - \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left(\{\mathbf{w}_h\} \cdot \mathbf{n} (\llbracket \mathbf{u}_h \rrbracket \cdot \{\!|\mathbf{v}_h|^2\!\}) + \frac{1}{2} \llbracket \mathbf{w}_h \rrbracket \cdot \mathbf{n} \{\!|\mathbf{u}_h \cdot \mathbf{v}_h|\!\} \right) \, ds \\ &= \int_{\Omega} \left((\mathbf{w}_h \cdot \nabla_h \mathbf{u}_h) \cdot \mathbf{v}_h + \frac{1}{2} \operatorname{div}_h(\mathbf{w}_h) \mathbf{u}_h \cdot \mathbf{v}_h \right) \, dx - \frac{1}{2} \int_{\partial \Omega} (\mathbf{w}_h \cdot \mathbf{n}) \mathbf{u}_h \cdot \mathbf{v}_h \, ds \\ &\quad - \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left(\{\mathbf{w}_h\} \cdot \mathbf{n} (\llbracket \mathbf{u}_h \rrbracket \cdot \{\!|\mathbf{v}_h|^2\!\}) + \frac{1}{2} \llbracket \mathbf{w}_h \rrbracket \cdot \mathbf{n} \{\!|\mathbf{u}_h \cdot \mathbf{v}_h|\!\} \right) \, ds \quad (3.7) \end{aligned}$$

This expression has been proposed by Pietro and Ern [5, p. 22], eqn (72) (see also [6, p. 272], eqn (6.57)). The boundary term introduced in t_h may be compensated in the right-hand side:

$$l_h^*(\mathbf{v}) := l_h(\mathbf{v}) - \frac{Re}{2} \int_{\partial \Omega} (\mathbf{g} \cdot \mathbf{n}) \mathbf{g} \cdot \mathbf{v}_h \, ds$$

Notice that the boundary term introduced in t_h is compensated in the right-hand side l_h^* .

Example file 3.5: inertia.icc

```

1  template<class W, class U, class V>
2  form inertia (W w, U u, V v,
3    quadrature_option_type qopt = quadrature_option_type())
4  {
5    return
6    integrate (dot(grad_h(u)*w,v) + 0.5*div_h(w)*dot(u,v), qopt)
7    + integrate ("boundary", - 0.5*dot(w,normal())*dot(u,v), qopt)
8    + integrate ("internal_sides",
9      - dot(average(w),normal())*dot(jump(u),average(v))
10     - 0.5*dot(jump(w),normal())
11     *(dot(average(u),average(v)) + 0.25*dot(jump(u),jump(v))), qopt);
12 }
13 field inertia_fix_rhs (test v,
14   quadrature_option_type qopt = quadrature_option_type())
15 {
16   return integrate("boundary", - 0.5*dot(g(),normal())*dot(g(),v), qopt);
17 }

```

The discrete problem is

$(FV)_h$: find $\mathbf{u}_h \in \mathbf{X}_h$ and $p \in Q_h$ such that

$$\begin{aligned}
 Ret_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + a_h(\mathbf{u}_h, \mathbf{v}_h) + b_h(\mathbf{v}_h, p_h) &= l_h^*(\mathbf{v}_h), \forall \mathbf{v}_h \in \mathbf{X}_h, \\
 b_h(\mathbf{u}_h, q_h) - c_h(p_h, q_h) &= k_h(q), \forall q_h \in Q_h
 \end{aligned} \tag{3.8}$$

The simplest approach for solving the discrete problem is to consider a fixed-point algorithm. The sequence $(\mathbf{u}_h^{(k)})_{k \geq 0}$ is defined by recurrence as:

- $k = 0$: let $\mathbf{u}_h^{(0)} \in \mathbf{X}_h$ being known.
- $k \geq 0$: let $\mathbf{u}_h^{(k-1)} \in \mathbf{X}_h$ given. Find $\mathbf{u}_h^{(k)} \in \mathbf{X}_h$ and $p_h^{(k)} \in Q_h$ such that

$$\begin{aligned}
 Ret_h(\mathbf{u}_h^{(k-1)}; \mathbf{u}_h^{(k)}, \mathbf{v}_h) + a_h(\mathbf{u}_h^{(k)}, \mathbf{v}_h) + b_h(\mathbf{v}_h, p_h^{(k)}) &= l_h^*(\mathbf{v}_h), \forall \mathbf{v}_h \in \mathbf{X}_h, \\
 b_h(\mathbf{u}_h^{(k)}, q_h) - c_h(p_h^{(k)}, q_h) &= k_h(q), \forall q_h \in Q_h.
 \end{aligned}$$

At each step $k \geq 0$, this algorithm involves a linear subproblem of Stokes-type.

Example file 3.6: navier_stokes_taylor_dg.cc

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 #include "taylor.icc"
5 #include "stokes_dirichlet_dg.icc"
6 #include "inertia.icc"
7 int main(int argc, char**argv) {
8     environment rheolef (argc, argv);
9     geo omega (argv[1]);
10    space Xh (omega, argv[2], "vector");
11    space Qh (omega, argv[2]);
12    Float Re      = (argc > 3) ? atof(argv[3]) : 1;
13    size_t max_iter = (argc > 4) ? atoi(argv[4]) : 1;
14    form a, b, c, mp;
15    field lh, kh;
16    stokes_dirichlet_dg (Xh, Qh, a, b, c, mp, lh, kh);
17    field uh (Xh, 0), ph (Qh, 0);
18    solver_abtb stokes (a.uu(), b.uu(), c.uu(), mp.uu());
19    stokes.solve (lh.u(), kh.u(), uh.set_u(), ph.set_u());
20    trial u (Xh); test v (Xh);
21    form a1 = a + Re*inertia (uh, u, v);
22    lh += Re*inertia_fix_rhs (v);
23    derr << "#k r as" << endl;
24    for (size_t k = 0; k < max_iter; ++k) {
25        solver_abtb stokes (a1.uu(), b.uu(), c.uu(), mp.uu());
26        stokes.solve (lh.u(), kh.u(), uh.set_u(), ph.set_u());
27        form th = inertia (uh, u, v);
28        a1 = a + Re*th;
29        field rh = a1*uh + b.trans_mult(ph) - lh;
30        derr << k << " " << rh.max_abs() << " " << th(uh,uh) << endl;
31    }
32    dout << catchmark("Re") << Re << endl
33         << catchmark("u") << uh
34         << catchmark("p") << ph;
35 }

```

Comments

The data are given when $d = 2$ by (3.1). This choice is convenient since the exact solution is known $\mathbf{u} = \mathbf{g}$ and $p = -(Re/4)(\cos(2\pi x_0) + \cos(2\pi x_1))$. The code `navier_stokes_taylor_error_dg.cc` compute the error in L^2 , L^∞ and energy norms. This code it is not listed here but is available in the **Rheolef** example directory. The computation writes:

```

make navier_stokes_taylor_dg navier_stokes_taylor_error_dg
./navier_stokes_taylor_dg square P1d 10 10 | ./navier_stokes_taylor_error_dg
./navier_stokes_taylor_dg square P2d 10 10 | ./navier_stokes_taylor_error_dg

```

3.3.3 A conservative variant

Remark the identity

$$\operatorname{div}(\mathbf{u} \otimes \mathbf{u}) = (\mathbf{u} \cdot \nabla) \mathbf{u} + \operatorname{div}(\mathbf{u}) \mathbf{u}$$

The momentum conservation can be rewritten in conservative form and the problem writes:

(\tilde{P}): find \mathbf{u} and p , defined in Ω , such that

$$\begin{aligned} \operatorname{div}(Re \mathbf{u} \otimes \mathbf{u} - 2D(\mathbf{u})) + \nabla p &= \mathbf{f} \text{ in } \Omega, \\ -\operatorname{div} \mathbf{u} &= 0 \text{ in } \Omega, \\ \mathbf{u} &= \mathbf{g} \text{ on } \partial\Omega \end{aligned}$$

Notice the Green formulae (see volume 1, appendix A.2, page 141):

$$\int_{\Omega} \mathbf{div}(\mathbf{u} \otimes \mathbf{u}) \cdot \mathbf{v} \, dx = - \int_{\Omega} (\mathbf{u} \otimes \mathbf{u}) : \nabla \mathbf{v} \, dx + \int_{\partial\Omega} (\mathbf{u} \cdot \mathbf{n}) (\mathbf{u} \cdot \mathbf{v}) \, ds$$

The variationnal formulation is:

(\widetilde{FV}): find $\mathbf{u} \in \mathbf{V}(\mathbf{g})$ and $p \in L^2(\Omega)$ such that

$$\begin{aligned} \operatorname{Re} \tilde{t}(\mathbf{u}; \mathbf{u}, \mathbf{v}) + a(\mathbf{u}, \mathbf{v}) + b(\mathbf{v}, p) &= \tilde{l}(\mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{V}(0), \\ b(\mathbf{u}, q) &= 0, \quad \forall q \in L^2(\Omega) \end{aligned}$$

where the forms \tilde{t} and \tilde{l}_h are given by:

$$\begin{aligned} \tilde{t}(\mathbf{w}; \mathbf{u}, \mathbf{v}) &= - \int_{\Omega} (\mathbf{w} \otimes \mathbf{u}) : \nabla \mathbf{v} \, dx \\ \tilde{l}(\mathbf{v}) &= l(\mathbf{v}) - \operatorname{Re} \int_{\partial\Omega} (\mathbf{g} \cdot \mathbf{n}) (\mathbf{g} \cdot \mathbf{v}) \, ds \end{aligned}$$

Notice that the right-hand side \tilde{l} contains an additional term that compensates those coming from the integration by parts. Then, with $\mathbf{v} = \mathbf{u}$:

$$\begin{aligned} \tilde{t}(\mathbf{w}; \mathbf{u}, \mathbf{u}) &= - \int_{\Omega} (\mathbf{w} \otimes \mathbf{u}) : \nabla \mathbf{u} \, dx \\ &= \int_{\Omega} \mathbf{div}(\mathbf{w} \otimes \mathbf{u}) \cdot \mathbf{u} \, dx - \int_{\partial\Omega} (\mathbf{w} \otimes \mathbf{u}) : (\mathbf{u} \otimes \mathbf{n}) \, dx \\ &= \int_{\Omega} (((\mathbf{u} \cdot \nabla) \mathbf{w}) \cdot \mathbf{u} + \operatorname{div}(\mathbf{u}) (\mathbf{u} \cdot \mathbf{w})) \, dx - \int_{\partial\Omega} (\mathbf{u} \cdot \mathbf{n}) (\mathbf{u} \cdot \mathbf{w}) \, dx \end{aligned}$$

From an integration by part similar to (3.4):

$$\int_{\Omega} (\mathbf{u} \cdot \nabla \mathbf{w}) \cdot \mathbf{u} \, dx = - \int_{\Omega} (\mathbf{u} \cdot \nabla \mathbf{u}) \cdot \mathbf{w} \, dx - \int_{\Omega} \operatorname{div}(\mathbf{u}) (\mathbf{u} \cdot \mathbf{w}) \, dx + \int_{\partial\Omega} (\mathbf{u} \cdot \mathbf{n}) (\mathbf{u} \cdot \mathbf{w}) \, ds$$

The term $(\mathbf{u} \cdot \nabla \mathbf{w}) \cdot \mathbf{u}$ do not reapper after the integration by parts: instead, it appears $(\mathbf{u} \cdot \nabla \mathbf{u}) \cdot \mathbf{w}$. Thus, the structure of the \tilde{t} trilinear form do not permit a general skew-symmetry property as it was the case for t . It requires the three arguments to be the same:

$$\tilde{t}(\mathbf{u}; \mathbf{u}, \mathbf{u}) = \int_{\Omega} (((\mathbf{u} \cdot \nabla) \mathbf{u}) \cdot \mathbf{u} + \operatorname{div}(\mathbf{u}) |\mathbf{u}|^2) \, dx - \int_{\partial\Omega} (\mathbf{u} \cdot \mathbf{n}) |\mathbf{u}|^2 \, ds$$

Using (3.4) with $\mathbf{w} = \mathbf{u}$ leads to:

$$\int_{\Omega} ((\mathbf{u} \cdot \nabla) \mathbf{u}) \cdot \mathbf{u} \, dx = - \frac{1}{2} \int_{\Omega} \operatorname{div}(\mathbf{u}) |\mathbf{u}|^2 \, dx + \frac{1}{2} \int_{\partial\Omega} (\mathbf{u} \cdot \mathbf{n}) |\mathbf{u}|^2 \, ds \quad (3.9)$$

Then

$$\tilde{t}(\mathbf{u}; \mathbf{u}, \mathbf{u}) = \frac{1}{2} \int_{\Omega} \operatorname{div}(\mathbf{u}) |\mathbf{u}|^2 \, dx - \frac{1}{2} \int_{\partial\Omega} (\mathbf{u} \cdot \mathbf{n}) |\mathbf{u}|^2 \, ds$$

When working with velocities that are not divergence-free, a possible modification of the trilinear form \tilde{t} is to consider

$$\begin{aligned} \tilde{t}^*(\mathbf{w}; \mathbf{u}, \mathbf{v}) &= \tilde{t}(\mathbf{w}; \mathbf{u}, \mathbf{v}) - \frac{1}{2} \int_{\Omega} \operatorname{div}(\mathbf{v}) (\mathbf{u} \cdot \mathbf{w}) \, dx + \frac{1}{2} \int_{\partial\Omega} (\mathbf{v} \cdot \mathbf{n}) (\mathbf{u} \cdot \mathbf{w}) \, ds \\ &= - \int_{\Omega} \left((\mathbf{w} \otimes \mathbf{u}) : D(\mathbf{v}) + \frac{1}{2} \operatorname{div}(\mathbf{v}) (\mathbf{u} \cdot \mathbf{w}) \right) \, dx + \frac{1}{2} \int_{\partial\Omega} (\mathbf{v} \cdot \mathbf{n}) (\mathbf{u} \cdot \mathbf{w}) \, ds \end{aligned}$$

Then we have

$$\tilde{t}^*(\mathbf{u}; \mathbf{u}, \mathbf{u}) = 0, \quad \forall \mathbf{u} \in H^1(\Omega)^d$$

The new variational formulation is:

$(\widetilde{FV})^*$: find $\mathbf{u} \in \mathbf{V}(\mathbf{g})$ and $\tilde{p} \in L^2(\Omega)$ such that

$$\begin{aligned} Re \tilde{t}^*(\mathbf{u}; \mathbf{u}, \mathbf{v}) + a(\mathbf{u}, \mathbf{v}) + b(\mathbf{v}, \tilde{p}) &= \tilde{l}(\mathbf{v}), \quad \forall \mathbf{v} \in \mathbf{V}(0), \\ b(\mathbf{u}, q) &= 0, \quad \forall q \in L^2(\Omega) \end{aligned}$$

One can easily check that when (\mathbf{u}, \tilde{p}) is a solution of $(\widetilde{FV})^*$, then (\mathbf{u}, p) is a solution of (\widetilde{FV}) with $p = \tilde{p} + Re|\mathbf{u}|/2$. The apparition of the kinetic energy term $Re|\mathbf{u}|/2$ in the modified pressure field \tilde{p} is due to the introduction of the $\text{div}(\mathbf{v})(\mathbf{u} \cdot \mathbf{w})$ term in the trilinear form \tilde{t}^* .

At the discrete level, let us define for all $\mathbf{u}_h, \mathbf{v}_h, \mathbf{w}_h \in \mathbf{X}_h$:

$$\begin{aligned} \tilde{t}_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) &= - \int_{\Omega} \left((\mathbf{w}_h \otimes \mathbf{u}_h) : \nabla_h \mathbf{v}_h + \frac{1}{2} \text{div}_h(\mathbf{v}_h)(\mathbf{u}_h \cdot \mathbf{w}_h) \right) dx \\ &\quad + \frac{1}{2} \int_{\partial\Omega} (\mathbf{v}_h \cdot \mathbf{n})(\mathbf{u}_h \cdot \mathbf{w}_h) ds \end{aligned}$$

Notice that \tilde{t}_h^* is similar to \tilde{t}^* : the gradient and divergence has been replaced by their broken counterpart in the first term. As $\mathbf{X}_h \not\subset H^1(\Omega)^d$, the skew-symmetry property is not expected to be true at the discrete level. Then

$$\tilde{t}_h^*(\mathbf{u}_h; \mathbf{u}_h, \mathbf{u}_h) = - \int_{\Omega} \left((\mathbf{u}_h \otimes \mathbf{u}_h) : \nabla_h \mathbf{u}_h + \frac{1}{2} \text{div}_h(\mathbf{u}_h)|\mathbf{u}_h|^2 \right) dx + \frac{1}{2} \int_{\partial\Omega} (\mathbf{u}_h \cdot \mathbf{n})|\mathbf{u}_h|^2 ds$$

Next, using (3.9) in each K , and then developing thanks to (3.5)-(3.6), we get

$$\begin{aligned} \tilde{t}_h^*(\mathbf{u}_h; \mathbf{u}_h, \mathbf{u}_h) &= \frac{1}{2} \int_{\partial\Omega} (\mathbf{u}_h \cdot \mathbf{n})|\mathbf{u}_h|^2 ds - \frac{1}{2} \sum_{K \in \mathcal{T}_h} \int_{\partial K} (\mathbf{u}_h \cdot \mathbf{n})|\mathbf{u}_h|^2 ds \\ &= -\frac{1}{2} \sum_{S \in \mathcal{S}_h^{(i)}} \int_S [(\mathbf{u}_h \cdot \mathbf{n})|\mathbf{u}_h|^2] ds \\ &= -\frac{1}{2} \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left((\{\mathbf{u}_h\} \cdot \mathbf{n}) [|\mathbf{u}_h|^2] + ([\mathbf{u}_h] \cdot \mathbf{n}) \{\{|\mathbf{u}_h|^2\}\} \right) ds \\ &= - \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left((\{\mathbf{u}_h\} \cdot \mathbf{n}) (\{\mathbf{u}_h\} \cdot [\mathbf{u}_h]) + \frac{1}{2} ([\mathbf{u}_h] \cdot \mathbf{n}) \{\{|\mathbf{u}_h|^2\}\} \right) ds \end{aligned}$$

The idea is to integrate this term in the definition of a discrete \tilde{t}_h . One of the possibilities is

$$\begin{aligned} \tilde{t}_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) &= \tilde{t}_h^*(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) + \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left((\{\mathbf{u}_h\} \cdot \mathbf{n}) (\{\mathbf{w}_h\} \cdot [\mathbf{v}_h]) + \frac{1}{2} \{\mathbf{u}_h \cdot \mathbf{w}_h\} ([\mathbf{v}_h] \cdot \mathbf{n}) \right) ds \\ &= - \int_{\Omega} \left((\mathbf{w}_h \otimes \mathbf{u}_h) : \nabla_h \mathbf{v}_h + \frac{1}{2} \text{div}_h(\mathbf{v}_h)(\mathbf{u}_h \cdot \mathbf{w}_h) \right) dx \\ &\quad + \frac{1}{2} \int_{\partial\Omega} (\mathbf{v}_h \cdot \mathbf{n})(\mathbf{u}_h \cdot \mathbf{w}_h) ds \\ &\quad + \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \left((\{\mathbf{u}_h\} \cdot \mathbf{n}) (\{\mathbf{w}_h\} \cdot [\mathbf{v}_h]) + \frac{1}{2} \{\mathbf{u}_h \cdot \mathbf{w}_h\} ([\mathbf{v}_h] \cdot \mathbf{n}) \right) ds \end{aligned} \quad (3.10)$$

This expression was proposed by [5, p. 21], eqn (73) (see also [6, p. 282]) following and original idea introduced in [3].

Example file 3.7: inertia_cks.icc

```

1 form inertia (field w, trial u, test v,
2   quadrature_option_type qopt = quadrature_option_type())
3 {
4   return
5     integrate (- dot(trans(grad_h(v))*w,u) - 0.5*div_h(v)*dot(u,w), qopt)
6   + integrate ("internal_sides",
7     dot(average(u),normal())*dot(jump(v),average(w))
8     + 0.5*dot(jump(v),normal())
9     *(dot(average(u),average(w)) + 0.25*dot(jump(u),jump(w))), qopt)
10  + integrate ("boundary", 0.5*dot(v,normal())*dot(u,w), qopt);
11 }
12 field inertia_fix_rhs (test v,
13   quadrature_option_type qopt = quadrature_option_type())
14 {
15   return integrate("boundary", -dot(g(),normal())*dot(g(),v), qopt);
16 }

```

The discrete problem is

$(\widetilde{FV})_h$: find $\mathbf{u}_h \in \mathbf{X}_h$ and $\tilde{p} \in Q_h$ such that

$$\begin{aligned} Re \tilde{t}_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + a_h(\mathbf{u}_h, \mathbf{v}_h) + b_h(\mathbf{v}_h, \tilde{p}_h) &= \tilde{l}_h^*(\mathbf{v}_h), \forall \mathbf{v}_h \in \mathbf{X}_h, \\ b_h(\mathbf{u}_h, q_h) - c_h(p_h, q_h) &= k_h(q), \forall q_h \in Q_h \end{aligned}$$

A simple test program is obtained by replacing in `navier_stokes_taylor_dg.cc` the include `inertia.icc` by `inertia_cks.icc`. The compilation and run are similar.

3.3.4 A Newton solver

The discrete problems $(FV)_h$ can be put in a compact form:

$$F(\mathbf{u}_h, p_h) = 0$$

where F is defined in variational form:

$$\langle F(\mathbf{u}_h, p_h), (\mathbf{v}_h, q_h) \rangle = \left(\begin{array}{cccc} Re t_h(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + a_h(\mathbf{u}_h, \mathbf{v}_h) + b_h(\mathbf{v}_h, p_h) - l_h^*(\mathbf{v}_h) \\ b_h(\mathbf{u}_h, q_h) - c_h(p_h, q_h) - k_h(q) \end{array} \right)$$

for all $(\mathbf{v}_h, q_h) \in \mathbf{X}_h \times Q_h$. Notices that, after some minor modifications in the definition of F , this method could also applies for the locally conservative formulation $(\widetilde{FV})_h$. The previous formulation is simply the variational expression of $F(\mathbf{u}_h, p_h) = 0$. The Newton method defines the sequence $(\mathbf{u}_h^{(k)})_{k \geq 0}$ by recurrence as:

- $k = 0$: let $\mathbf{u}_h^{(0)} \in \mathbf{X}_h$ being known.
- $k \geq 0$: let $\mathbf{u}_h^{(k-1)} \in \mathbf{X}_h$ given. Find $\delta \mathbf{u}_h \in \mathbf{X}_h$ and $\delta p_h \in Q_h$ such that

$$F'(\mathbf{u}_h^{(k-1)}, p_h^{(k-1)}) \cdot (\delta \mathbf{u}_h, \delta p_h) = -F(\mathbf{u}_h^{(k-1)}, p_h^{(k-1)})$$

and then defines

$$\mathbf{u}_h^{(k)} = \mathbf{u}_h^{(k-1)} + \delta \mathbf{u}_h \quad \text{and} \quad p_h^{(k)} = p_h^{(k-1)} + \delta p_h$$

At each step $k \geq 0$, this algorithm involves a linear subproblem involving the jacobian F' that is defined by its variational form:

$$\begin{aligned} &\langle F'(\mathbf{u}_h^{(k-1)}, p_h^{(k-1)}) \cdot (\delta \mathbf{u}_h, \delta p_h), (\mathbf{v}_h, q_h) \rangle \\ &= \left(\begin{array}{ccc} Re (t_h(\delta \mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + t_h(\mathbf{u}_h; \delta \mathbf{u}_h, \mathbf{v}_h)) + a_h(\delta \mathbf{u}_h, \mathbf{v}_h) + b_h(\mathbf{v}_h, \delta p_h) \\ b_h(\delta \mathbf{u}_h, q_h) - c_h(\delta p_h, q_h) \end{array} \right) \end{aligned}$$

Example file 3.8: navier_stokes_taylor_newton_dg.cc

```

1 #include "rheolef.h"
2 using namespace rheolef;
3 using namespace std;
4 #include "taylor.icc"
5 #include "stokes_dirichlet_dg.icc"
6 #include "inertia.icc"
7 #include "navier_stokes_dg.h"
8 int main(int argc, char**argv) {
9     environment rheolef (argc, argv);
10    Float eps = numeric_limits<Float>::epsilon();
11    geo omega (argv[1]);
12    string approx = (argc > 2) ? argv[2] : "P1d";
13    Float Re = (argc > 3) ? atof(argv[3]) : 100;
14    Float tol = (argc > 4) ? atof(argv[4]) : eps;
15    size_t max_iter = (argc > 5) ? atoi(argv[5]) : 100;
16    string restart = (argc > 6) ? argv[6] : "";
17    navier_stokes_dg F (Re, omega, approx);
18    navier_stokes_dg::value_type xh = F.initial (restart);
19    int status = damped_newton (F, xh, tol, max_iter, &derr);
20    dout << catchmark("Re") << Re << endl
21         << catchmark("u") << xh[0]
22         << catchmark("p") << xh[1];
23    return status;
24 }

```

Comments

The implementation of the Newton method follows the generic approach introduced in volume 1, section 8.3, page 126. For that purpose we define a class `navier_stokes_dg`.

Example file 3.9: navier_stokes_dg.h

```

1 struct navier_stokes_dg {
2     typedef valarray<field> value_type;
3     typedef Float float_type;
4     navier_stokes_dg (Float Re, const geo& omega, string approx);
5     value_type initial (string restart) const;
6     value_type residue (const value_type& uh) const;
7     void update_derivative (const value_type& uh) const;
8     value_type derivative_solve (const value_type& mrh) const;
9     value_type derivative_trans_mult (const value_type& mrh) const;
10    Float space_norm (const value_type& uh) const;
11    Float dual_space_norm (const value_type& mrh) const;
12    Float duality_product (const value_type& mrh, const value_type& msh) const;
13    Float Re;
14    space Xh, Qh;
15    quadrature_option_type qopt;
16    form a0, b, c, mu, mp;
17    field lh0, lh, kh;
18    solver smu, smp;
19    mutable form a1;
20    mutable solver_abtb stokes1;
21 };
22 #include "navier_stokes_dg1.icc"
23 #include "navier_stokes_dg2.icc"

```

The member functions of the class are defined in two separate files.

Example file 3.10: navier_stokes_dg1.icc

```

1  navier_stokes_dg::navier_stokes_dg (
2  Float Re1, const geo& omega, string approx)
3  : Re(Re1), Xh(), Qh(), qopt(), a0(), b(), c(), mu(), mp(), lh0(), lh(), kh(),
4  smu(), smp(), a1(), stokes1()
5  {
6  Xh = space (omega, approx, "vector");
7  Qh = space (omega, approx);
8  qopt.set_family(quadrature_option_type::gauss);
9  qopt.set_order(2*Xh.degree()+1);
10 stokes_dirichlet_dg (Xh, Qh, a0, b, c, mp, lh0, kh, qopt);
11 trial u (Xh); test v (Xh);
12 lh = lh0 + Re*inertia_fix_rhs (v, qopt);
13 mu = integrate (dot(u,v), qopt);
14 smu = solver(mu.uu());
15 smp = solver(mp.uu());
16 }
17 navier_stokes_dg::value_type
18 navier_stokes_dg::initial (string restart) const {
19 value_type xh(2);
20 xh[0] = field (Xh, 0);
21 xh[1] = field (Qh, 0);
22 Float Re0 = 0;
23 if (restart == "") {
24 solver_abtb stokes0 (a0.uu(), b.uu(), c.uu(), mp.uu());
25 stokes0.solve (lh0.u(), kh.u(), xh[0].set_u(), xh[1].set_u());
26 } else {
27 idiststream in (restart);
28 in >> catchmark("Re") >> Re0
29 >> catchmark("u") >> xh[0]
30 >> catchmark("p") >> xh[1];
31 check_macro (xh[1].get_space() == Qh, "unexpected " << xh[0].get_space().stamp()
32 << " approximation in file \"" << restart << "\" (" << Xh.stamp() << " expected)");
33 }
34 derr << "# continuation: from Re=" << Re0 << " to " << Re << endl;
35 return xh;
36 }
37 navier_stokes_dg::value_type
38 navier_stokes_dg::residue (const value_type& xh) const {
39 trial u (Xh); test v (Xh);
40 form a = a0 + Re*inertia(xh[0], u, v, qopt);
41 value_type mrh(2);
42 mrh[0] = a*xh[0] + b.trans_mult(xh[1]) - lh;
43 mrh[1] = b*xh[0] - c*xh[1] - kh;
44 return mrh;
45 }
46 void navier_stokes_dg::update_derivative (const value_type& xh) const {
47 trial u (Xh); test v (Xh);
48 a1 = a0 + Re*(inertia(xh[0], u, v, qopt) + inertia(u, xh[0], v, qopt));
49 stokes1 = solver_abtb (a1.uu(), b.uu(), c.uu(), mp.uu());
50 }
51 navier_stokes_dg::value_type
52 navier_stokes_dg::derivative_solve (const value_type& mrh) const {
53 value_type delta_xh(2);
54 delta_xh[0] = field (Xh, 0);
55 delta_xh[1] = field (Qh, 0);
56 stokes1.solve (mrh[0].u(), mrh[1].u(),
57 delta_xh[0].set_u(), delta_xh[1].set_u());
58 return delta_xh;
59 }
60 navier_stokes_dg::value_type
61 navier_stokes_dg::derivative_trans_mult (const value_type& mrh) const {
62 value_type rh(2);
63 rh[0] = field (Xh);
64 rh[1] = field (Qh);
65 rh[0].set_u() = smu.solve(mrh[0].u());
66 rh[1].set_u() = smp.solve(mrh[1].u());
67 value_type mgh(2);
68 mgh[0] = a1.trans_mult(rh[0]) + b.trans_mult(rh[1]);
69 mgh[1] = b*rh[0] - c*rh[1];
70 return mgh;
71 }

```

Example file 3.11: navier_stokes_dg2.icc

```

1  Float navier_stokes_dg::dual_space_norm (const value_type& mrh) const {
2    value_type rh(2);
3    rh[0] = field (Xh);
4    rh[1] = field (Qh);
5    rh[0].set_u() = smu.solve(mrh[0].u());
6    rh[1].set_u() = smp.solve(mrh[1].u());
7    return std::max(rh[0].max_abs(), rh[1].max_abs());
8  }
9  Float navier_stokes_dg::space_norm (const value_type& xh) const {
10   return sqrt (mu(xh[0],xh[0]) + mp(xh[1],xh[1]));
11 }
12 Float navier_stokes_dg::duality_product (
13   const value_type& mrh, const value_type& msh) const
14 {
15   value_type rh(2);
16   rh[0] = field (Xh);
17   rh[1] = field (Qh);
18   rh[0].set_u() = smu.solve(mrh[0].u());
19   rh[1].set_u() = smp.solve(mrh[1].u());
20   return dual (rh[0], msh[0]) + dual (rh[1], msh[1]);
21 }

```

```

make navier_stokes_taylor_newton_dg navier_stokes_taylor_error_dg
./navier_stokes_taylor_newton_dg square P2d 1000 | ./navier_stokes_taylor_error_dg

```

3.3.5 Application to the driven cavity benchmark

Example file 3.12: cavity_dg.icc

```

1  struct g: field_functor<g,point> {
2    point operator() (const point& x) const {
3      return point((abs(1-x[1]) < 1e-7) ? 1 : 0, 0, 0); }
4  };
5  struct f: field_functor<f,point> {
6    point operator() (const point& x) const { return point(0,0,0); }
7  };

```

The program `navier_stokes_cavity_newton_dg.cc` is obtained by replacing in `navier_stokes_taylor_newton_dg.cc` the include `taylor.icc` by `cavity_dg.icc` that defines the boundary conditions. The compilation and run are similar.

```

make navier_stokes_cavity_newton_dg stream_cavity
./navier_stokes_cavity_newton_dg square P1d 500 > square.field
field -proj square.field -field | ./streamf_cavity | \
    field -bw -n-iso-negative 10 -mayavi -

```

3.3.6 Upwinding

The skew symmetry property is generalized to the requirement that t_h be non-dissipative (see [6, p. 282], eqn (6.68)):

$$t_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{u}_h) \geq 0, \forall \mathbf{w}_h, \mathbf{u}_h \in \mathbf{X}_h$$

A way to satisfy this property is to add an *upwinding* term in t_h :

$$\check{t}_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) := t_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) + s_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h)$$

with

$$s_h(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) = \frac{1}{2} \sum_{S \in \mathcal{S}_h^{(i)}} \int_S |\{\{\mathbf{w}_h\}\}.n| (\llbracket \mathbf{u}_h \rrbracket \cdot \llbracket \mathbf{v}_h \rrbracket) ds$$

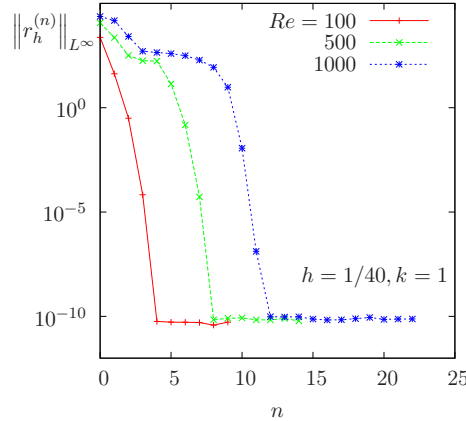


Figure 3.1: The discontinuous Galerkin method for the Navier-Stokes problem on the driven cavity benchmark when $k = 1$ and $d = 2$: convergence of the damped Newton algorithm.

We aim at using a Newton method. We replace t_h by its extension \check{t}_h containing the upwind terms in the definition of F , and then we compute its jacobian F' . As the absolute value is not differentiable, the functions s_h , \check{t}_h and then F are also not differentiable with respect to \mathbf{w}_h . Nevertheless, the absolute value is convex and we can use some concepts of the subdifferential calculus. Let us introduce the multi-valued sign function:

$$\text{sgn}(x) = \begin{cases} \{1\} & \text{when } x > 0 \\ [-1, 1] & \text{when } x = 0 \\ \{-1\} & \text{when } x < 0 \end{cases}$$

Then, the subdifferential of the absolute value function is $\text{sgn}(x)$ and for all $\delta\mathbf{w}_h, \mathbf{w}_h, \mathbf{u}_h, \mathbf{v}_h \in \mathbf{X}_h$, we define a generalization of the partial derivative as

$$\frac{\partial s_h}{\partial \mathbf{w}_h}(\mathbf{w}_h; \mathbf{u}_h, \mathbf{v}_h) \cdot (\delta\mathbf{w}_h) = \frac{1}{2} \sum_{S \in \mathcal{S}_h^{(i)}} \int_S \text{sgn}(\{\{\mathbf{w}_h\}\} \cdot \mathbf{n}) (\{\{\delta\mathbf{w}_h\}\} \cdot \mathbf{n}) (\{\{\mathbf{u}_h\}\} \cdot \{\{\mathbf{v}_h\}\}) \, ds$$

Example file 3.13: inertia_upw.icc

```

1 #include "sgn.icc"
2 form inertia_upw (field w, trial u, test v,
3   quadrature_option_type qopt = quadrature_option_type())
4 {
5   return integrate ("internal_sides",
6     0.5*abs(dot(average(w), normal()))*dot(jump(u), jump(v)));
7 }
8 form d_inertia_upw (field w, trial dw, field u, test v,
9   quadrature_option_type qopt = quadrature_option_type())
10 {
11   return integrate ("internal_sides",
12     0.5*compose (sgn, dot(average(w), normal()))
13     *dot(average(dw), normal())*dot(jump(u), jump(v)));
14 }

```

A multi-valued jacobian F' is then defined:

$$\begin{aligned} & \langle F' \left(\mathbf{u}_h^{(k-1)}, p_h^{(k-1)} \right), (\delta \mathbf{u}_h, \delta p_h), (\mathbf{v}_h, q_h) \rangle \\ &= \operatorname{Re} \left(\begin{array}{c} t_h(\delta \mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) + t_h(\mathbf{u}_h; \delta \mathbf{u}_h, \mathbf{v}_h) + \frac{\partial s_h}{\partial \mathbf{w}_h}(\mathbf{u}_h; \mathbf{u}_h, \mathbf{v}_h) \cdot (\delta \mathbf{u}_h) + s_h(\mathbf{u}_h; \delta \mathbf{u}_h, \mathbf{v}_h) \\ 0 \end{array} \right) \\ &+ \left(\begin{array}{cc} a_h(\delta \mathbf{u}_h, \mathbf{v}_h) & + \quad b_h(\mathbf{v}_h, \delta p_h) \\ b_h(\delta \mathbf{u}_h, q_h) & - \quad c_h(\delta p_h, q_h) \end{array} \right) \end{aligned}$$

We are able to extend the Newton method to the F function that allows a multi-valued subdifferential F' . During iterations, we can choose any of the available directions in the subdifferential. One the possibilities is then to replace the multi-valued sign function by a single-value one:

$$\widetilde{\operatorname{sgn}}(x) = \begin{cases} 1 & \text{when } x \geq 0 \\ -1 & \text{when } x < 0 \end{cases}$$

Example file 3.14: `sgn.icc`

```
1 Float sgn (Float x) { return (x >= 0) ? 1 : -1; }
```

Example file 3.15: `navier_stokes_upw_dg.h`

```
1 #include "navier_stokes_dg.h"
2 struct navier_stokes_upw_dg: navier_stokes_dg {
3     typedef valarray<field> value_type;
4     typedef Float float_type;
5     navier_stokes_upw_dg (Float Re, const geo& omega, string approx);
6     value_type residue (const value_type& uh) const;
7     void update_derivative (const value_type& uh) const;
8 };
9 #include "navier_stokes_upw_dg.icc"
```

Example file 3.16: `navier_stokes_upw_dg.icc`

```
1 #include "inertia_upw.icc"
2 navier_stokes_upw_dg::navier_stokes_upw_dg (
3     Float Re1, const geo& omega, string approx)
4     : navier_stokes_dg (Re1, omega, approx) {}
5
6 navier_stokes_upw_dg::value_type
7 navier_stokes_upw_dg::residue (const value_type& xh) const {
8     trial u (Xh); test v (Xh);
9     form a = a0 + Re*( inertia (xh[0], u, v, qopt)
10         + inertia_upw (xh[0], u, v, qopt));
11     value_type mrh(2);
12     mrh[0] = a*xh[0] + b.trans_mult(xh[1]) - lh;
13     mrh[1] = b*xh[0] - c*xh[1] - kh;
14     return mrh;
15 }
16 void navier_stokes_upw_dg::update_derivative (const value_type& xh) const {
17     trial du (Xh); test v (Xh);
18     a1 = a0 + Re*( inertia (xh[0], du, v, qopt)
19         + inertia_upw (xh[0], du, v, qopt)
20         + inertia (du, xh[0], v, qopt)
21         + d_inertia_upw (xh[0], du, xh[0], v, qopt));
22     stokes1 = solver_abtb (a1.uu(), b.uu(), c.uu(), mp.uu());
23 }
```

The program `navier_stokes_cavity_newton_upw_dg.cc` is obtained by replacing in `navier_stokes_taylor_newton_dg.cc` the string `navier_stokes_dg` by `navier_stokes_upw_dg` (two occurrences: in the includes and then in the definition of F). Also replace the include `taylor.icc` by `cavity_dg.icc` that defines the boundary conditions. The compilation and run are similar.

```

make navier_stokes_cavity_newton_upw_dg stream_cavity
mkgeo_grid -t 80 > square.geo
./navier_stokes_cavity_newton_upw_dg square P1d 500 1e-15 100 > square-500.field
field -proj square-500.field -field | ./streamf_cavity | \
    field -bw -n-iso 30 -n-iso-negative 20 -mayavi -

```

Computations for higher Reynolds numbers are performed by continuation, starting from a previous computation at lower Re :

```

./navier_stokes_cavity_newton_upw_dg square P1d 1000 1e-15 100 square-500.field > square-1000.fi
./navier_stokes_cavity_newton_upw_dg square P1d 1500 1e-15 100 square-1000.field > square-1500.fi

```

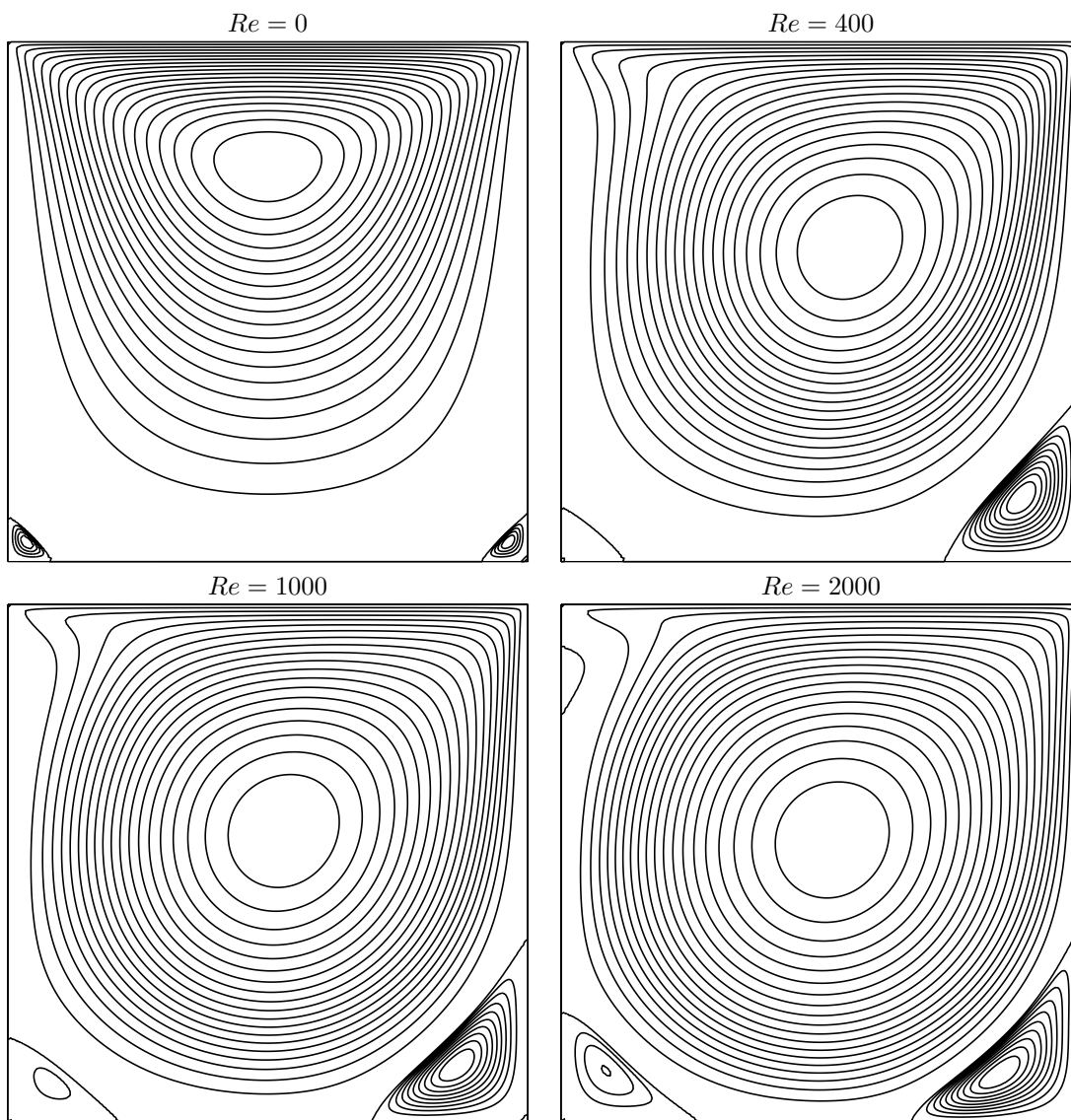


Figure 3.2: The discontinuous Galerkin method for the Navier-Stokes problem on the driven cavity benchmark when $k = 1$ (80×80 grid): stream function isovalues for various Re .

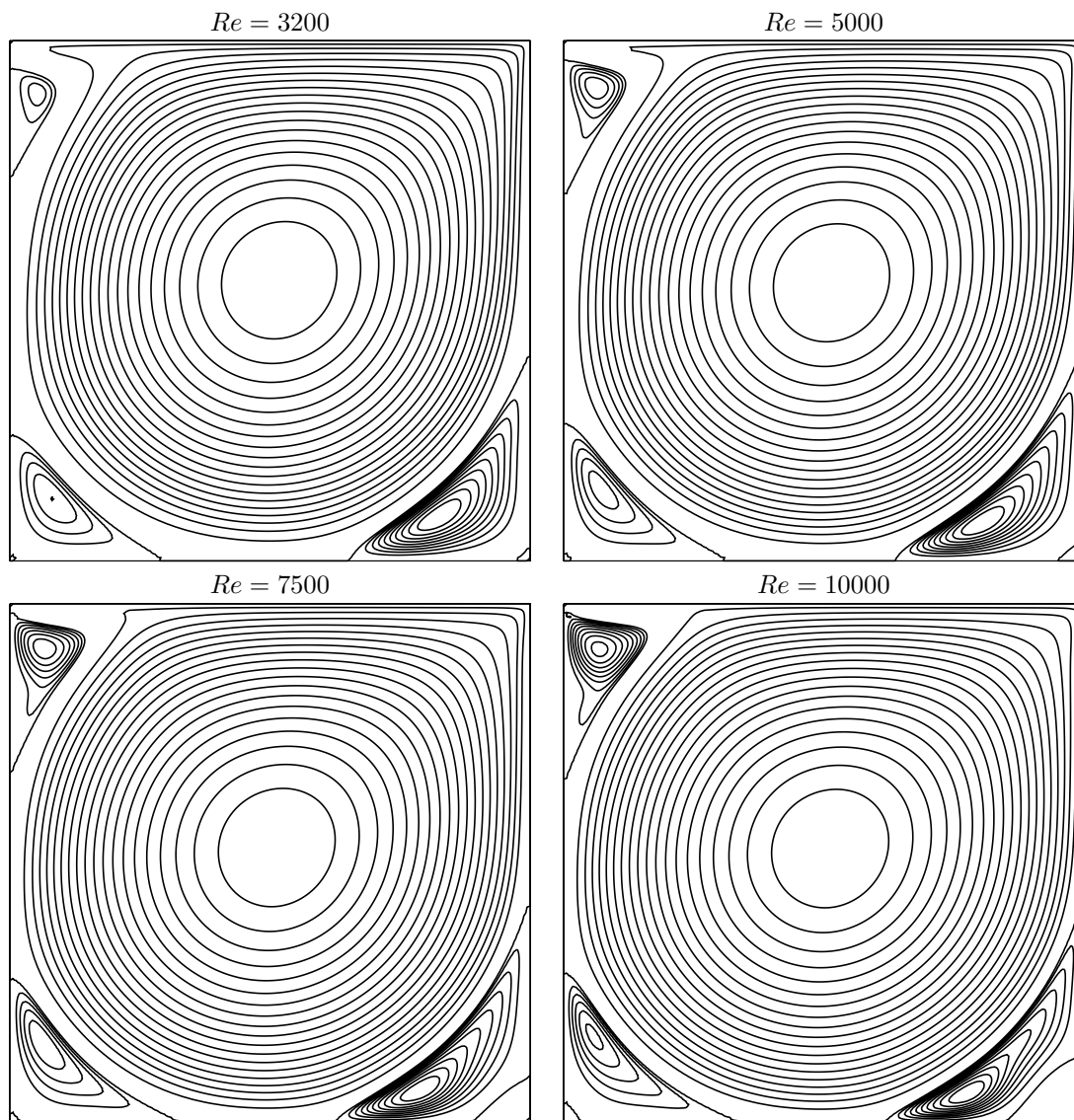


Figure 3.3: The discontinuous Galerkin method for the Navier-Stokes problem on the driven cavity benchmark when $k = 1$ (80×80 grid): stream function isovalues for various Re (cont.).

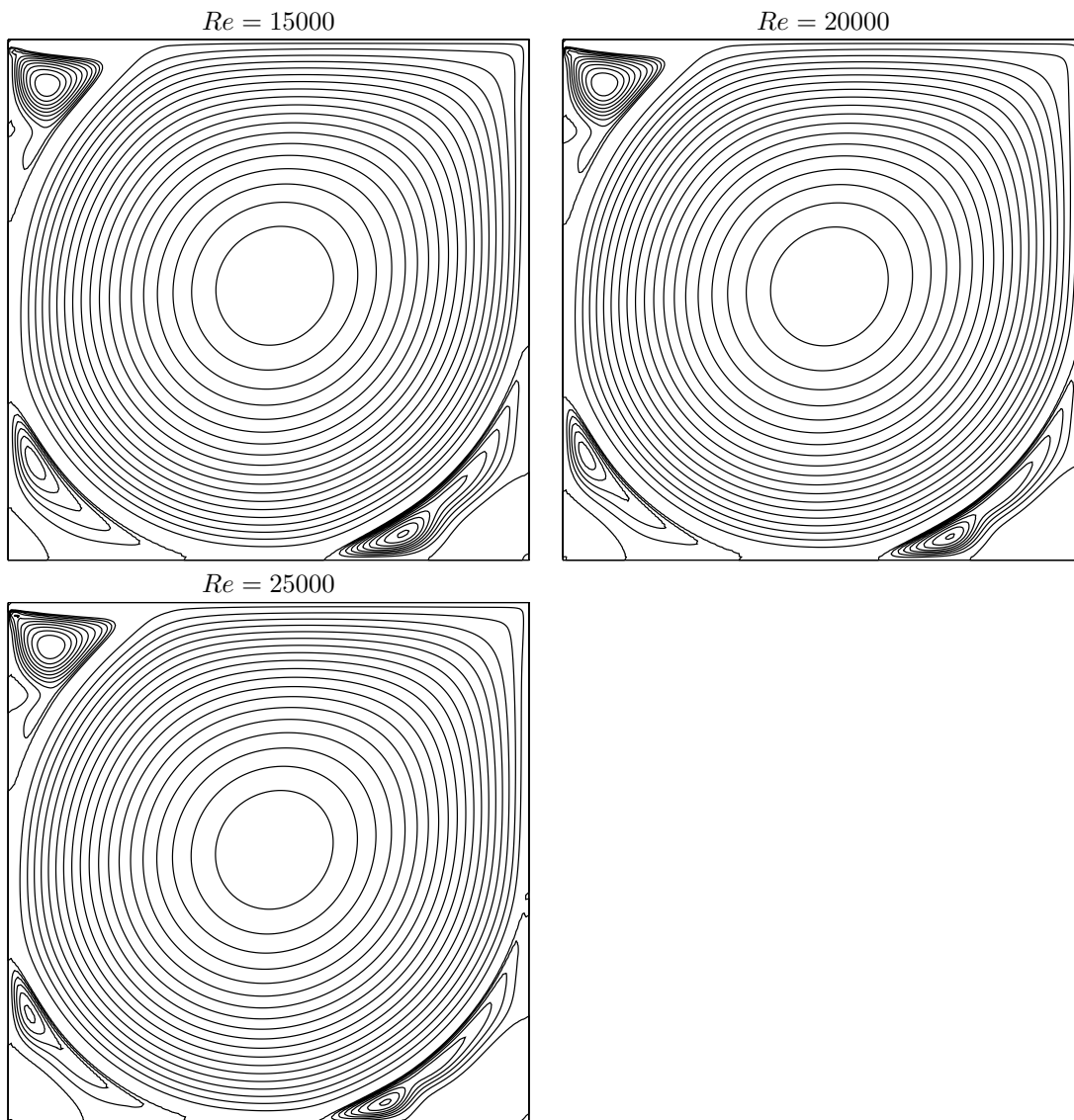


Figure 3.4: The discontinuous Galerkin method for the Navier-Stokes problem on the driven cavity benchmark when $k = 1$ (80×80 grid): stream function isovalues for various Re (cont.).

Part III

Technical appendices

Appendix A

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