An arbitrary-order fully discrete Stokes complex on general polygonal meshes.

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May 12, 2022

Abstract

In this paper we present an arbitrary-order fully discrete Stokes complex on general polygonal meshes. Based upon the recent construction of the de Rham fully discrete complex [14] we extend it using the same principle. We complete it with other polynomial spaces related to vector calculus operators and to the Koszul complex required to accommodate the increased smoothness of the Stokes complex. This complex is especially well suited for problem involving Jacobian, divergence and curl, like e.g. the Stokes system or magnetohydrodynamics. We show a complete set of results on the novelties of this complex complementing those of [14]: exactness properties, uniform Poincaré inequalities and primal and adjoint consistency. We use our new complex on the Stokes system and validate the expected convergence rates with various numerical tests.

Keywords: Discrete Stokes complex, Discrete de Rham complex, compatible discretization, polytopal methods

MSC2010 classification: 65N30, 65N99, 76D07

1 Introduction.

The exactness of the divergence free condition plays an important role in the numerical resolution of incompressible fluid equations, [6] provides a detailed review. This kind of conservation requires the discrete spaces to reproduce relevant algebraic properties of the continuous spaces. This exactness can be expressed as a differential complex.

\[
\mathbb{R} \xrightarrow{i_{\Omega}} H^1(\Omega) \xrightarrow{\text{rot}} H(\text{div}, \Omega) \xrightarrow{\text{div}} L^2(\Omega) \xrightarrow{0} \{0\}
\] (1.1)

Many discrete counterparts of the complex (1.1) have been developed. See [7] for a thorough exposition and an extensive bibliography. Although many partial differential equations can be expressed using the de Rham complex, the lack of smoothness can cause issues for some equations. In particular with the Stokes equations (see [3]). So a smoother variant more suited to the Stokes equations and called Stokes complex has been considered. It is written in two dimensions:

\[
\mathbb{R} \xrightarrow{i_{\Omega}} H^2(\Omega) \xrightarrow{\text{rot}} H^1(\Omega) \xrightarrow{\text{div}} L^2(\Omega) \xrightarrow{0} \{0\}
\] (1.2)
The development of discrete counterparts of this smoother complex is much more complicated. See [7, Chapter 8.7] for a history. Although such construction exits (for example [5]) they often have drawbacks. Recurrent problems can be a large minimal degree and thus numerous unknowns as well as difficulties to enforce Dirichlet boundary conditions. The subject is very active with many recent advances: [11, 12]. Another issue of these constructions is that they are frequently constrained to conformal simplicial meshes, which is limiting for some geometries as well as on the possibility of refinement or agglomeration. A construction of the Stokes complex in virtual finite elements on general meshes has also been recently developed (see [13]).

Our construction works on general polygonal meshes and for arbitrary degrees. The discrete spaces consist of polynomial spaces on the elements of all dimensions: faces, edges and vertices. Compared to the virtual finite element method, the basis functions are explicitly known but do not live in a subspace of continuous functions. The discrete differential operators are therefore necessarily different from the continuous operators. They are constructed according to integration by parts formulas and in a sense converge with the discrete spaces to the continuous operators (see the consistency results of Section 5). A discretization of the de Rham complex (1.1) has been developed in detail by D. A. Di Pietro and J. Droniou [14]. One can find in the introduction a very complete comparison of the different methods leading to discrete de Rham complex on polytopal meshes. Our paper is a continuation of [14]: Our construction is based upon it, and we add the necessary basis functions required by the increased smoothness of the Stokes complex. We define and analyze in detail the Jacobian operator while checking its compatibility with the complex.

More precisely we show the exactness of the complex, the existence of uniform Poincare inequality and many consistency results as well as a discrete version of the right inverse for the divergence for the discrete norm $H^1$. This complex aims to be a building block for a three-dimensional variation, but it is also perfectly usable for two-dimensional problems. Finally, we apply this to the Stokes equations: we show the well-posedness, give an error estimate and find an optimal convergence rate of order $O(h^{k+1})$, $h$ being the size of the mesh and $k \geq 0$ the chosen polynomial degree. We also explore other choices of boundary conditions and validate numerically every result.

The remaining of the paper is organized as follows. In Section 2 we establish the general setting. We define the discrete spaces and operators (interpolators, differential operators and norms) in Section 3. In Section 4 we show that we do indeed belong to a complex which is exact for simply connected domains. Section 5 is dedicated to consistency properties. Including primal and dual consistency. The Stokes equations are defined in Section 6 and other boundary conditions are studied in 7. We display our numerical results in Section 8. Finally we prove technical propositions in the appendices: on polynomial spaces in appendix A and on various lift in appendix B.

2 Setting.

This section is dedicated to the introduction of the setting and various notations that will be used throughout the paper.

2.1 Mesh and orientation.

In the following we consider a polytopal domain $\Omega \subset \mathbb{R}^2$ and keeping the notation of [14], for any set $Y \subset \mathbb{R}^2$, we write $h_Y := \sup \{|x-y|: x, y \in Y\}$ and $|Y|$ its Hausdorff measure. We consider on this domain a mesh sequence $\mathcal{M}_h = \mathcal{F}_h \cup \mathcal{E}_h \cup \mathcal{V}_h$ parameterized by a positive real
parameter \( h \in \mathcal{H} \). Here \( \mathcal{F}_h \) is a finite collection of open convex polygon such that \( \overline{\Omega} = \bigcup_{F \in \mathcal{F}_h} F \) and \( h = \max_{F \in \mathcal{F}_h} h_F > 0 \), \( \mathcal{E}_h \) is the collection of open polygonal edges of the faces, \( \mathcal{V}_h \) the collection of edge vertices. This sequence must be regular in the sense of [10, Definition 1.9] with the regularity constant \( \rho \).

We take \( k \geq 0 \) a fixed polynomial degree. In the following most inequalities are true up to a positive constant. This constant depends only on some parameters, here on the chosen polynomial degree \( k \), on the regularity parameter of the mesh sequence \( \rho \) and on the domain \( \Omega \).

We denote the inequality up to a positive constant by

\[
A \lesssim B
\]

meaning there exists \( C \in \mathbb{R}_+^* \) depending only on some parameters (here usually only on \( k \), \( \rho \) and \( \Omega \)) such that \( A \leq CB \). We also write

\[
A \approx B
\]

meaning that \( A \lesssim B \) and \( B \lesssim A \).

For a fixed \( h \), we choose an orientation of the plane, and we fix for each edge \( E \in \mathcal{E}_h \) an orientation \( t_E \). We note by \( \perp \) the rotation of angle \( \pi/2 \) in the oriented plane and \( n_E = t_E \perp \).

For any face \( F \in \mathcal{F}_h \) we fix a counter-clockwise orientation of its boundary \( \partial F \). And for any edge of this face \( E \in \mathcal{E}_F \) we note \( \omega_{FE} \in \{-1, 1\} \) the value such that \( \omega_{FE} t_E \) is oriented in the opposite direction of \( \partial F \). We can then check that \( \omega_{FE} n_E \) is the outgoing normal unit vector of \( F \). We also define \( n_\Omega \) as the outward pointing unit normal vector on the boundary \( \partial \Omega \).

### 2.2 Polynomial spaces.

For any entity \( X \in \{E, F\} \), we denote by \( \mathcal{P}^k(X) \) the set of polynomials of total degree at most \( k \) on \( X \), by \( \mathcal{P}^k(F) \) the set of polynomials with vector value in \( \mathbb{R}^2 \) on \( F \), and by \( \left( \mathcal{P}^k(X) \right)^2 \) the set of pairs of polynomials on \( X \) forming the rows of a matrix. We use the conventions \( \mathcal{P}^{-1}(X) := \{0\} \) and \( \mathcal{P}^{0,k}(X) := \{ P \in \mathcal{P}^k(X) : \int_X P = 0 \} \). We also define the broken polynomial space

\[
\mathcal{P}^k(X_h) := \{ P_h \in L^2(X_h) : \forall X \in X_h, P_h|_X \in \mathcal{P}^k(X) \}.
\]

(2.1)

As well as its continuous counterpart

\[
\mathcal{P}^k_c(X_h) := \{ P_h \in C^0(X_h) : \forall X \in X_h, P_h|_X \in \mathcal{P}^k(X) \}.
\]

(2.2)

**Remark 1.** Continuous polynomials can be characterized by their values at the interface and their lower order moments on the elements. An explicit construction is deduced from Lemma [40] in the context of edges we can see the isomorphism between \( \mathcal{P}^{k+2}(\mathcal{E}_h) \) and \( \mathcal{P}^k(\mathcal{E}_h) \times \mathbb{R}^{\mathcal{V}_h} \).

For the sake of readability we recall here two lemmas on the discrete spaces which will often be used in the following, they are respectively the [10, Lemma 1.28 and Lemma 1.32] (in a slightly more restrictive setting):

**Lemma 2.** Let \( X \) be an element of \( \mathcal{F}_h \cup \mathcal{E}_h \). Let \( l \) be a positive integer and a real number \( p \in [1, \infty] \) be fixed. Then, the following inequality holds: For all \( v \in \mathcal{P}^l(X) \),

\[
\| \nabla v \|_{L^p(X)} \lesssim h_X^{1/l} \| v \|_{L^p(X)},
\]

(2.3)

with hidden constant depending only on \( \rho \), \( l \) and \( p \).
Lemma 3. Let \( p \in [1, \infty] \) be a fixed real number and \( l \geq 0 \) be a fixed integer. Then for all \( h \in \mathcal{H} \), all \( F \in \mathcal{F}_h \), all \( E \in \mathcal{E}_h \), all \( v \in \mathcal{P}^l(F) \),

\[
\|v\|_{L^p(E)} \lesssim h_F^{-\frac{l}{p}} \|v\|_{L^p(F)}
\]  

(2.4)

with hidden constant depending only on \( \rho \), \( l \) and \( p \).

We will also use Koszul complements (see [14, Section 2.4]). We consider for any face \( F \in \mathcal{F}_h \) a point \( x_F \) such that \( B(x_F, \rho \epsilon F) \subset F \). Then we define the following subspace of \( \mathcal{P}^k(F) \):

\[
\mathcal{G}^k(F) := \text{grad} \mathcal{P}^{k+1}(F), \quad \mathcal{G}^{c,k}(F) := (x - x_F) \cdot \mathcal{P}^{k-1}(F),
\]

\[
\mathcal{R}^k(F) := \text{rot} \mathcal{P}^{k+1}(F), \quad \mathcal{R}^{c,k}(F) := (x - x_F) \cdot \mathcal{P}^{k-1}(F).
\]  

(2.5)

These spaces are such that:

\[
\mathcal{P}^k(F) = \mathcal{G}^k(F) \oplus \mathcal{G}^{c,k}(F) = \mathcal{R}^k(F) \oplus \mathcal{R}^{c,k}(F),
\]  

(2.6)

however the sum is not orthogonal for the \( L^2 \) scalar product. We also have the following isomorphisms:

\[
\text{rot} : \mathcal{P}^{0,k}(F) \to \mathcal{R}^{k-1}(F),
\]

(2.7)

\[
\text{div} : \mathcal{R}^{c,k}(F) \to \mathcal{P}^{k-1}(F).
\]  

(2.8)

We may deduce from the discrete Poincare inequality Lemma 2 that \( \|\text{rot}\| \lesssim h^{-1} \), \( \|\text{div}\| \lesssim h^{-1} \) and from [14, Lemma 46] that \( \|\text{rot}^{-1}\| \lesssim h \), \( \|(\text{div})^{-1}\| \lesssim h \).

We define the local spaces of Nedelec and of Raviart-Thomas respectively by:

\[
\mathcal{N}^k(F) := \mathcal{G}^{k-1}(F) \oplus \mathcal{G}^{c,k}(F), \quad \mathcal{RT}^k(F) := \mathcal{R}^{k-1}(F) \oplus \mathcal{R}^{c,k}(F).
\]  

(2.9)

These spaces are strictly contained between \( \mathcal{P}^{k-1}(F) \) and \( \mathcal{P}^k(F) \). Another important property given in [14, Proposition 45] is that for any face \( F \in \mathcal{F}_h \) and any edge of this face \( E \in \mathcal{E}_F \):

\[
\forall v_F \in \mathcal{N}^k(F), (v_F)_{|E} \cdot t_E \in \mathcal{P}^{k-1}(E),
\]

\[
\forall w_F \in \mathcal{RT}^k(F), (w_F)_{|E} \cdot n_E \in \mathcal{P}^{k-1}(E).
\]  

(2.10)

In order to fix the notation we write

\[
(\mathcal{R}^{c,k}(F)^\dagger)^2 = \begin{pmatrix} \mathcal{R}^{c,k}(F)^\dagger \end{pmatrix}^T.
\]  

(2.11)

And we take differential operators to be acting row-wise on matrix valued functions. We define the space \( \overline{\mathcal{R}}^{c,k}(F) \) by

\[
\overline{\mathcal{R}}^{c,k}(F) := \{ W \in (\mathcal{R}^{c,k}(F)^\dagger)^2 : \text{Tr}W = 0 \}.
\]  

(2.12)

An explicit description of this space is given by Lemma 35. Let us now construct a complement to this space. First noticing that \( \text{Tr}((\mathcal{R}^{c,k}(F)^\dagger)^2) = \mathcal{P}^{0,k}(F) \) we can consider the inverse operator \( P^{k}_\text{Tr} : \mathcal{P}^{0,k}(F) \to (\mathcal{R}^{c,k}(F)^\dagger)^2 ; \)

\[
P^{k}_\text{Tr} := \begin{pmatrix} \text{div}^{-1} \\ \text{div}^{-1} \end{pmatrix} \circ \text{grad},
\]  

(2.13)

where \( \text{div} \) is the isomorphism from \( \mathcal{R}^{c,k}(F) \) into \( \mathcal{P}^{k-1}(F) \) given by (2.8). Then we define the space:

\[
\overline{\mathcal{R}}^k(F) := P^{k}_\text{Tr} \mathcal{P}^{0,k}(F).
\]  

(2.14)

Lemma 37 shows that the spaces \( \overline{\mathcal{R}}^{c,k}(F) \) and \( \overline{\mathcal{R}}^k(F) \) are complementary.
Remark 4. By construction, we have: $\nabla \cdot \mathcal{R}^k(F) = \nabla \cdot P_{\nabla}^k P^0(F) = \text{grad } P^k(F)$.

Remark 5. These spaces are hierarchical since $\mathcal{R}^{c,k} \subset \mathcal{R}^{c,k+1}$, $\mathcal{R}^k \subset \mathcal{R}^{k+1}$.

We define a matrix valued equivalent to Raviart-Thomas space by
\[
\mathcal{RT}^k(F) := \mathcal{R}^{c,k}(F) \oplus (\mathcal{R}^k(F)^T)^2.
\]

Remark 6. These spaces are hierarchical since $\mathcal{R}^{c,k} \subset \mathcal{R}^{c,k+1}$, $\mathcal{R}^k \subset \mathcal{R}^{k+1}$.

We define a matrix valued equivalent to Raviart-Thomas space by
\[
\mathcal{RT}^k(F) := \mathcal{R}^{c,k}(F) \oplus (\mathcal{R}^k(F)^T)^2.
\]

Lemma 7. For $x_F \in F$ the point given by (2.5) we have $\nabla \cdot \mathcal{R}^{c,k+1}(F) = (x - x_F)^\bot P^{k-1}(F)$.

Proof. Indeed by Lemma 35 we have
\[
\mathcal{R}^{c,k+1}(F) = \begin{pmatrix}
-x \cdot x_F & -y \cdot y_F \\
(x-x_F)^2 Q & (x-x_F)(y-y_F) Q
\end{pmatrix}, Q \in P^{k-1}(F),
\]
\[
\nabla \cdot \mathcal{R}^{c,k+1}(F) = \begin{pmatrix}
-(y-y_F)^2 Q & -(y-y_F)^2 Q \\
(x-x_F)(y-y_F) Q & (x-x_F)(y-y_F) Q
\end{pmatrix}, Q \in P^{k-1}(F).
\]

\[ \square \]

3 Discrete complex.

We define now the discrete complex. We start by giving all the elements composing it with the locations of their degrees of freedom. Then we define the discrete differential operators and give some basic properties on them. To distinguish operators acting on scalar from those acting on vector we use the notation $\text{grad}$ for the operator from scalar fields to vector fields and $\nabla$ for the operator acting on vector fields and giving a tensor field.

3.1 Complex definition.

We define four discrete spaces $X_{\text{rot}}^k$, $X_{\nabla}^k$, $X_{L^2}^{k+1}$, and $X_{L^2}^k$. The diagram (3.1) summarize their connection with each other and with their continuous counterpart.

\[
\begin{align*}
H^2(\Omega) & \xrightarrow{\text{rot}} H^1(\Omega) \xrightarrow{\text{div}} L^2(\Omega) \xrightarrow{\nabla} \mathcal{R}^{c,k}(F) \\
X_{\text{rot}}^k & \xrightarrow{\nabla} X_{\nabla}^k \xrightarrow{\Delta} X_{L^2}^{k+1} \xrightarrow{\nabla} X_{L^2}^k
\end{align*}
\]
Operators.

Figure 1 summarize the involvement of the various degrees of freedom with the differential in 3.1. Discrete spaces are defined by:

\[ F : \quad \mathcal{P}^{k-1}(F) \xrightarrow{\text{rot}} \mathcal{G}^{k-1}(F) \times \mathcal{G}^{c,k}(F) \xrightarrow{\text{div}} \mathcal{P}^{k}(F) \]

\[ E : \quad \mathcal{P}^{k}(E) \xrightarrow{\text{Id}} \mathcal{P}^{k-1}(E) \xrightarrow{\text{rot}} \mathcal{P}^{k}(E) \xrightarrow{\nabla} \mathcal{P}^{k+1}(E) \]

\[ V : \quad \mathbb{R} = \mathcal{P}^{k+1}(V) \quad \mathcal{P}^{k+2}(V) \xrightarrow{\text{Id}} \mathbb{R}^2 = \mathcal{P}^{k+2}(V) \]

Figure 1: Usage of the local degrees of freedom for the discrete differential operators.

Notice that the interpolators (defined in 3.2) require more smoothness than the spaces shown in 3.1. Discrete spaces are defined by:

\[
X^k_{\text{rot},h} := \{ q_h = ((q_v, R_q)_{E \in \mathcal{E}_h}, (R_q)_{V \in \mathcal{V}_h}, (q_F)_{F \in \mathcal{F}_h}) : q_E \in \mathcal{P}^{k+1}_c(\mathcal{E}_h), \]
\[ R_q, E \in \mathcal{P}^{k}(E), \forall E \in \mathcal{E}_h, \]
\[ R_q, V \in \mathbb{R}^2, \forall V \in \mathcal{V}_h, \]
\[ q_F \in \mathcal{P}^{k-1}(F), \forall F \in \mathcal{F}_h \}, \quad (3.2) \]

\[
X^k_{\nabla,h} := \{ v_h = ((v_v)_{E \in \mathcal{E}_h}, (v_{g,F}, v_{\nabla,F})_{F \in \mathcal{F}_h}) : v_E \in \mathcal{P}^{k+2}_c(\mathcal{E}_h), \]
\[ v_{g,F} \in \mathcal{G}^{k-1}(F), v_{\nabla,F} \in \mathcal{G}^{c,k}(F), \forall F \in \mathcal{F}_h \}, \quad (3.3) \]

\[
X^{k+1}_{L^2,h} := \{ w_h = ((w_v)_{E \in \mathcal{E}_h}, (w_F)_{F \in \mathcal{F}_h}) : w_E \in \mathcal{P}^{k+1}(E), \forall E \in \mathcal{E}_h, \]
\[ w_F \in \mathcal{R}\mathcal{T}^{k+1}(F), \forall F \in \mathcal{F}_h \}, \quad (3.4) \]

\[
X^k_{L^2,h} := \{ w_h = ((w_F)_{F \in \mathcal{F}_h}) : w_F \in \mathcal{P}^{k}(F), \forall F \in \mathcal{F}_h \}. \quad (3.5) \]

Figure 1 summarize the involvement of the various degrees of freedom with the differential operators.

For a given face \( F \) we define the local discrete spaces \( X^k_{\text{rot},F}, X^k_{\nabla,F}, X^k_{L^2,F} \) and \( X^{k+1}_{L^2,F} \) as the restriction of the global one to \( F \), i.e. containing only the components attached to \( F \) and those attached to the edges and vertices lying on its boundary. We define in the same way the local discrete spaces attached to an edge \( E \).

### 3.2 Interpolators.

In this section we define the interpolator linking discrete spaces to their continuous counterpart. Since we project on objects of lower dimension (edges and vertices) we will need a somewhat high smoothness for the continuous functions. For a vertex \( V \in \mathcal{V}_h \) we define \( x_V \in \mathbb{R}^2 \) to be its coordinate. The interpolator on the space \( X^k_{\text{rot},h} \) is defined for any \( q \in C^1(\overline{\Omega}) \) by

\[
I^k_{\text{rot},h}q = ((q_v, \pi_{\mathcal{P},E}(\text{rot} q \cdot t_E))_{E \in \mathcal{E}_h}, (\text{rot} q(V))_{V \in \mathcal{V}_h}, (\pi_{\mathcal{P},F}(q))_{F \in \mathcal{F}_h}), \quad (3.6) \]
where for any edge \( E \in \mathcal{E}_h \), \( q_E \) is such that \( \pi_{P,E}^{k-1}(q_E) = \pi_{P,E}^{k-1}(q) \) and for any vertex \( V \in \mathcal{V}_E \), \( q_E(x_V) = q(x_V) \).

The interpolator on the space \( X_{L^h}^k \) is defined for any \( v \in C^0(\Omega) \) by
\[
\mathbb{I}_{L^h}^k v = ((v_E)_{E \in \mathcal{E}_h}, (\pi_{Q,F}^{k-1}(v), \pi_{Q,F}^k(v))_{F \in \mathcal{F}_h}).
\]
(3.7)
where for any edge \( E \in \mathcal{E}_h \), \( v_E \) is such that \( \pi_{P,E}^k(v_E) = \pi_{P,E}^k(v) \) and for any vertex \( V \in \mathcal{V}_E \), \( v_E(x_V) = v(x_V) \).

The interpolator on the space \( X_{L^h}^{k+1} \) is defined for any \( W \in (C^0(\Omega))^2 \) by
\[
\mathbb{I}_{L^h}^{k+1} W = ((\pi_{P,E}^{k+1}(W \cdot t_E))_{E \in \mathcal{E}_h}, (\pi_{R,F}^{k+1}(W))_{F \in \mathcal{F}_h}).
\]
(3.8)

The interpolator on the space \( X_{L^h}^{k+1} \) is just \( \pi_{X,F}^k \), the piecewise \( L^2 \)-orthogonal projection on spaces \( P^k(F), F \in \mathcal{F}_h \).

### 3.3 Curl.

In the following sections we define the discrete operators starting from the discrete curl operator \( C_h^k \). The operator \( C_h^k \) is the collection of the local discrete operators (3.11) acting on the edges and faces. For any edge \( E \in \mathcal{E}_h \) we define the operator \( C_E : X_{rot,E}^k \rightarrow P_{c}^{k+2}(\mathcal{E}_h) \) such that
\[
\forall q_E = (q_E, R_{q,E}, (R_{q,V})_{V \in \mathcal{V}_E}) \in X_{rot,E}^k \quad \Rightarrow \quad C_E q_E = v_E,
\]
(3.9)
where \( v_E \) is such that \( \pi_{P,E}^k(v_E) = R_{q,E} t_E - q_E' n_E \) and \( \forall V \in \mathcal{V}_E, v_E(x_V) = R_{q,V} \). We write \( q_E' \) the derivative of \( q_E \) along the edge \( E \) (oriented by \( t_E \)).

For any face \( F \in \mathcal{F}_h \) we define the operator \( C_F^k : X_{rot,F}^k \rightarrow P^k(F) \) such that \( \forall q_F = ((q_E, R_{q,E})_{E \in \mathcal{E}_h}, (R_{q,V})_{V \in \mathcal{V}_F}, q_F) \in X_{rot,F}^k, \forall r_F \in P^k(F) \)
\[
\int_F C_F^k q_F \cdot r_F = \int q_F \cdot r_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E q_E r_F \cdot t_E.
\]
(3.10)

The full operator \( C_F^k : X_{rot,F}^k \rightarrow X_{rot,F}^k \) is defined as the collection and projection of the local operators. Explicitly for all \( q_{F_{1,2}} \in X_{rot,h}^k \)
\[
C_F^k q_{F_{1,2}} = ((C_E q_{F_{1,2}})_{E \in \mathcal{E}_F}, (\pi_{Q,F}^{k-1}(C_F q_{F_{1,2}}), \pi_{Q,F}^k(C_F q_{F_{1,2}}))_F).
\]
(3.11)

The global operator \( C_F^k \) is obtained by gathering the local operators \( C_F^k, F \in \mathcal{F}_h \).

### 3.4 Jacobian.

Likewise, we begin by defining the local operator on edges: \( \nabla_{E}^{k+1} : X_{rot,E}^k \rightarrow P^{k+1}(E) \) such that \( \forall v_E \in X_{rot,E}^k \)
\[
\nabla_{E}^{k+1} v_E = v_E'.
\]
(3.12)
The derivative is taken along the tangent \( t_E \) of the edge \( E \).

We define the local operator on faces: \( \nabla_{F}^{k+1} : X_{rot,F}^k \rightarrow \mathcal{RT}^{k+1}(F) \) such that \( \forall v_F \in X_{rot,F}^k \)
\[\forall W_F = W_{\mathcal{RT},F} + W_{\mathcal{R},F} + W_{\mathcal{R},F} \in \mathcal{RT}^{k+1}(F),\]
\[
\int_F \nabla_{F}^{k+1}(v_F) : W_F = - \int_F v_{\mathcal{G},F} \cdot \nabla \cdot (W_{\mathcal{G},F}) - \int_F v_{\mathcal{G},F} \cdot \nabla \cdot (W_{\mathcal{R},F}) + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E W_F n_E.
\]
(3.13)
Proof. The equation (3.16) is deduced exactly as it is done for [14, Equation 3.8]. Let prove (3.17): For all \( v \in H^1(F) \cap C^0(\overline{F}) \) and all \( W_F \in \mathcal{R}_h \),
\[
\int_F \nabla^{k+1}_F (\mathbf{I}^k_{\nabla,F} v) : \mathbf{W}_F = - \int_F \pi^{c,k}_{\mathbf{I}^k_{\nabla,F}}(v) \cdot \nabla \cdot (\mathbf{W}_F^c) - \int_F \pi^{k-1}_{\mathbf{I}^k_{\nabla,F}} v \cdot \nabla \cdot (\mathbf{W}_F^c) + \int_F vW_Fn_E.
\]
We used Lemma 7 and the definition (2.14) to remove the first two projections \( \pi^{c,k}_{\mathbf{I}^k_{\nabla,F}} \) and \( \pi^{k-1}_{\mathbf{I}^k_{\nabla,F}} \), the property (2.10) to remove the last projection and the integration by parts to conclude. □

Any face \( F \in \mathcal{F}_h \) has several polynomials attached to it (on the face itself and on its edges). In order to combine all these polynomials into a single one defined on \( F \) we introduce a reconstruction operator \( \gamma^{k+1}_{\nabla,F} : \mathbf{X}^k_{\nabla,F} \rightarrow (\mathcal{P}^{k+1}(F)\mathcal{T})^2 \) implicitly defined by the relation:
\[
\gamma^{k+1}_{\nabla,F} : \mathbf{X}^k_{\nabla,F} \rightarrow (\mathcal{P}^{k+1}(F)\mathcal{T})^2.
\]

The isomorphism (2.8) ensure the well-posedness.

Remark 10. The relation (3.18) also holds for all \( W_F \in (\mathcal{P}^k(F)\mathcal{T})^2 \). Indeed if \( W_F \) belongs to \( (\mathcal{R}^k(F)\mathcal{T})^2 \) then \( \nabla \cdot W_F = 0 \) and the left-hand side of (3.18) is null. And since \((\mathcal{R}^k(F)\mathcal{T})^2 \subset (\mathcal{P}^k(F)\mathcal{T})^2 \subset \mathcal{R}_h \) we can apply (3.13) to show that the right-hand side is also zero. Hence, the relation holds for all \((\mathcal{R}^k(F)\mathcal{T})^2 \subset (\mathcal{P}^k(F)\mathcal{T})^2 \).
Lemma 11 (Consistency properties). For all $F \in \mathcal{F}_h$ the following relations hold:

\begin{align}
\gamma^{k+1}_F(L^k_F v) &= v, \quad \forall v \in \mathcal{P}^{k+1}(F), \\
\pi^c_{G,F}(\gamma^{k+1}_F v_F) &= v^c_{G,F}, \\
\pi^{-1}_{G,F}(\gamma^{k+1}_F v_F) &= v_{G,F}, \quad \forall v_F \in \mathcal{X}^k_F.
\end{align}

Proof. Let us show \eqref{eq:3.19}: For any $v \in \mathcal{P}^{k+1}(F)$, since $\nabla v \in (\mathcal{P}^{k}(F))^\top \subset \mathcal{R}T^{k+1}$ the equation \eqref{eq:3.17} gives

$$\nabla \cdot (L^{k+1}_F v) = \nabla v.$$ 

Moreover $v|_E$ is continuous of degree $k+1 < k+2$ so by the definition \eqref{eq:3.18} we have for all $W_F \in (\mathcal{R}^{c,k+1}(F))^\top$:

$$\int_F \gamma^{k+1}_F(L^{k}_F v) \cdot \nabla \cdot W_F = -\int_F \nabla v : W_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v W_F n_E$$

where we used that \eqref{eq:2.12} for the last hence, \eqref{eq:3.18}: For any $W_F \in \mathcal{R}^{c,k+1}(F)$ we can follow the same steps and show that $\pi^c_{G,F}(\gamma^{k+1}_F v_F) = v^c_{G,F}$. Likewise for all $W_F \in (\mathcal{R}^{c,k+2}(F))^\top$:

\begin{align}
\int_F \pi^{c,k}_{G,F}(\gamma^{k+1}_F v_F) \cdot \nabla \cdot W_F &= \int_F (\gamma^{k+1}_F v_F) \cdot \nabla \cdot W_F \\
&= -\int_F \nabla v^{k+1}(v_F) : W_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E W_F n_E \\
&= \int_F v^c_{G,F} \cdot \nabla \cdot W_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E (v_E - v_E) W_F n_E,
\end{align}

where we used Lemma \ref{lem:7} to show the first equality, \eqref{eq:3.18} for the second and \eqref{eq:2.12} for the last hence, $\pi^{c,k}_{G,F}(\gamma^{k+1}_F v_F) = v^c_{G,F}$. Likewise for all $W_F \in \mathcal{P}^{k}(F) I_{2,2}$: we have $\nabla \cdot \mathcal{P}^{k}(F) I_{2,2} = \mathcal{G}^{k-1}(F)$. Since the relation \eqref{eq:3.18} holds thanks to Remark 10 and since $\mathcal{P}^{k}(F) \subset \mathcal{R}T^{k+1}(F)$ we can follow the same steps and show that $\pi^{k-1}_{G,F}(\gamma^{k+1}_F v_F) = \pi^{k-1}_{G,F}$. \hfill $\Box$

### 3.5 Divergence.

Finally, we define the discrete divergence operator, for all $F \in \mathcal{F}_h$ by:

$$D^k_F := \text{Tr} \nabla^{k+1}_F \in \mathcal{P}^{k}(F).$$

As in the continuous case the divergence is the trace of the gradient, but we can also define it by a formula mimicking the integration by parts:

$$\int_F D^k_F v_F w_F = \int_F \text{Tr}(\nabla^{k+1}_F v_F) w_F$$

\begin{align}
&= \int_F \nabla^{k+1}_F v_F : w_F I_{2,2} \\
&= -\int_F v_{G,F} \text{grad} w_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E \cdot n_E w_F,
\end{align}

where we used that $\mathcal{P}^{k}(F) I_{2,2} \subset \mathcal{T}^{k+1}(F)$ by Remark \ref{rem:6} We get the same definition as the one of the de Rham complex of \cite{14}.\\
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3.6 Discrete $L^2$-product.

We build scalar product on discrete spaces. They are made of the sum of the $L^2$ scalar product on each face and of a stabilization term taking the lower dimensional objects (edges and vertices) into account. First we define them locally for all $F \in \mathcal{F}_h$: For all $\mathbf{v}_F, \mathbf{w}_F \in \mathbf{X}_{k,F}^L$ we set

$$
(\mathbf{v}_F, \mathbf{w}_F)_{\nabla,F} = \int_F \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \cdot \gamma_{\nabla,F}^{k+1} \mathbf{w}_F + s_{\nabla,F} (\mathbf{v}_F, \mathbf{w}_F),
$$

$$
{s_{\nabla,F} (\mathbf{v}_F, \mathbf{w}_F) = \sum_{E \in \mathcal{E}_F} h_E (\gamma_{\nabla,F}^{k+1} \mathbf{v}_E - \mathbf{v}_E) \cdot (\gamma_{\nabla,F}^{k+1} \mathbf{w}_E - \mathbf{w}_E).}
$$

For all $\mathbf{V}_F, \mathbf{W}_F \in \mathbf{X}_{k+1}^{L^2,F}$ we set

$$
(\mathbf{V}_F, \mathbf{W}_F)_{L^2,F} = \int_F \mathbf{V}_F : \mathbf{W}_F + s_{L^2,F} (\mathbf{V}_F, \mathbf{W}_F).
$$

$$
{s_{L^2,F} (\mathbf{V}_F, \mathbf{W}_F) = \sum_{E \in \mathcal{E}_F} h_E (\mathbf{V}_F \cdot \mathbf{t}_E - \mathbf{V}_E) \cdot (\mathbf{W}_F \cdot \mathbf{t}_E - \mathbf{W}_E).}
$$

Global scalar products are then merely the sum of local scalar product over every face $F \in \mathcal{F}_h$. For all $\mathbf{v}_F \in \mathbf{X}_{k,F}^L$ and $\mathbf{W}_F \in \mathbf{X}_{k+1}^{L^2,F}$ the norm induced by this scalar product is denoted by:

$$
\| \mathbf{v}_F \|_{\nabla,F} = (\mathbf{v}_F, \mathbf{v}_F)_{\nabla,F}^{1/2}, \quad \| \mathbf{W}_F \|_{L^2,F} = (\mathbf{W}_F, \mathbf{W}_F)_{L^2,F}^{1/2}.
$$

We also define norms built from the sum over the objects of every dimension. For all $q_F \in \mathbf{X}_{r,\mathbf{rot},F}^k$ we define

$$
\| q_F \|_{\mathbf{rot},F}^2 = \| q_F \|_F^2 + \sum_{E \in \mathcal{E}_F} h_E \left( \| q_F \|_E^2 + h_E \| R_{q,E} \|_E^2 + \sum_{V \in \mathcal{V}_E} h_E^2 \| R_{q,V} \|^2 \right).
$$

For all $\mathbf{v}_F \in \mathbf{X}_{r,\mathbf{rot},F}^k$ we define

$$
\| \mathbf{v}_F \|_{\mathbf{rot},F}^2 = \| \mathbf{v}_F \|_F^2 + \| \mathbf{v}_F \|_E^2 + \sum_{E \in \mathcal{E}_F} h_E \| \mathbf{v}_E \|_E^2.
$$

For all $\mathbf{W}_F \in \mathbf{X}_{r,\mathbf{rot},F}^{k+1}$ we define

$$
\| \mathbf{W}_F \|_{L^2,F}^2 = \| \mathbf{W}_F \|_F^2 + \sum_{E \in \mathcal{E}_F} h_E \| \mathbf{W}_E \|_E^2.
$$

And for all $\mathbf{p}_F \in \mathbf{X}_{L^2,F}^k$ we define

$$
\| \mathbf{p}_F \|_{L^2,F}^2 = \| \mathbf{p}_F \|_F^2.
$$

We show the equivalence between the norm induced by (3.22) and (3.27) in Lemma 14 and the equivalence between those induced by (3.24) and (3.28) in Lemma 15.

We define the global norms over $\Omega$ as the sum of the local norms over every face $F \in \mathcal{F}_h$, i.e. $\| \mathbf{u}_h \|_{\nabla,h}^2 = \sum_{F \in \mathcal{F}_h} \| \mathbf{u}_F \|_{\nabla,F}^2$.

**Lemma 12** (Inverse Poincaré inequality). For all $F \in \mathcal{F}_h$ and all $\mathbf{v}_F \in \mathbf{X}_{k,F}^L$ it holds:

$$
\| \nabla^{k+1} \mathbf{v}_F \| \lesssim h^{-1} \| \mathbf{v}_F \|_{\nabla,F}.
$$
Proof. Let $F \in \mathcal{F}_h$ and $v_F \in X^k_{\nabla,F}$. We use the discrete inverse inequality \cite{10} Lemma 1.28 to show that:

\[
\|\nabla^{k+1} v_F\|^2 = \int_F \nabla^{k+1} v_F \cdot \nabla^{k+1} v_F \\
\lesssim \|v^c_{g,F}\| h^{-1} \|\nabla^{k+1} v_F\| + \|v_{g,F}\| h^{-1} \|\nabla^{k+1} v_F\| + \|v_E\| h^{-1} \|\nabla^{k+1} v_F\|_F \\
\lesssim h^{-1} \|\nabla^{k+1} v_F\| (\|v^c_{g,F}\| + \|v_{g,F}\| + \sum_{E \in \mathcal{E}_F} h^2 \|v_E\|).
\]

\[\square\]

Lemma 13 (Boundedness of local potential). For all $F \in \mathcal{F}_h$ and all $v_F \in X^k_{\nabla,F}$ it holds:

\[
\|\gamma^{k+1}_{\nabla,F} v_F\| \lesssim \|v_F\|_{\nabla,F} \quad \text{(3.30)}
\]

Proof. Let $F \in \mathcal{F}_h$, $v_F \in X^k_{\nabla,F}$, since $\gamma^{k+1}_{\nabla,F} v_F \in \mathcal{P}^{k+1}(F)$ there is $W_F \in (\mathcal{R}^e_{k+2}(F)^r)^2$ such that $\nabla \cdot W_F = \gamma^{k+1}_{\nabla,F} v_F$ hence:

\[
\|\gamma^{k+1}_{\nabla,F} v_F\| = \int_F \gamma^{k+1}_{\nabla,F} v_F \cdot \gamma^{k+1}_{\nabla,F} v_F \\
= \int_F \gamma^{k+1}_{\nabla,F} v_F \cdot \nabla \cdot W_F \\
= - \int_F \nabla^{k+1} v_F \cdot W_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E W_F n_E \\
\leq \|\nabla^{k+1} v_F\| \|W_F\| + \sum_{E \in \mathcal{E}_F} \|v_E\| \|W_F\|_E \\
\lesssim h^{-1} \|v_F\|_{\nabla,F} \|W_F\| + h^{-1} \sum_{E \in \mathcal{E}_F} h^2 \|v_E\| \|W_F\|_F \\
\lesssim h^{-1} \|W_F\| \|v_F\|_{\nabla,F},
\]

where we used the Cauchy-Schwarz inequality to get the fourth line, Lemma \cite{12} for the fifth, the discrete trace inequality \cite{10} Lemma 1.32 for the sixth. We can conclude since $\|W_F\| \lesssim h \|\gamma^{k+1}_{\nabla,F} v_F\|$ thanks to the upper bound on the operator norm of the isomorphism \cite{2.8}. \[\square\]

Lemma 14. It holds, for all $F \in \mathcal{F}_h$ and all $v_F \in X^k_{\nabla,F}$,

\[
\|v_F\|_{\nabla,F} \approx \|v_F\|_{\nabla,F}, \forall v_F \in X^k_{\nabla,F}.
\]

Proof. From the definitions \cite{3.22} and \cite{3.23} we have:

\[
\|v_F\|_{\nabla,F}^2 = \int_F \gamma^{k+1}_{\nabla,F} v_F \cdot \gamma^{k+1}_{\nabla,F} v_F + \sum_{E \in \mathcal{E}_F} h_E \|\gamma^{k+1}_{\nabla,F} v_F - v_F\|^2 \\
\lesssim \|\gamma^{k+1}_{\nabla,F} v_F\|^2 + \sum_{E \in \mathcal{E}_F} h_E (\|\gamma^{k+1}_{\nabla,F} v_F\|_E^2 + \|v_E\|^2) \\
\lesssim \|\gamma^{k+1}_{\nabla,F} v_F\|^2 + \sum_{E \in \mathcal{E}_F} h_E (h^{-1}_E \|\gamma^{k+1}_{\nabla,F} v_F\|_F^2 + h^{-1}_E \|v_F\|_{\nabla,F}^2) \\
\lesssim \|v_F\|_{\nabla,F}^2,
\]

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where we used (3.30) on the first line and the trace inequality Lemma 3 on the second.

Conversely, \( \| \mathbf{w}_F \|_{\nabla, F}^2 = \| \mathbf{v}_{\gamma,F} \|_{\nabla, F}^2 + \| \mathbf{v}_{\gamma,F} \|_{\nabla, F}^2 + \sum_{E \in \mathcal{E}_F} h_E \| \mathbf{v}_E \|_{\nabla, E}^2 \) by (3.27). We bound each term of the right-hand side:

\[
\| \mathbf{v}_E \|_{\nabla, E}^2 \leq \| \mathbf{v}_E - \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, E}^2 + \| \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, E}^2 \\
\leq \| \mathbf{v}_E - \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, E}^2 + h_F^{-1} \| \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, E}^2.
\]

\[
\sum_{E \in \mathcal{E}_F} h_E \| \mathbf{v}_E \|_{\nabla, E}^2 \leq \| \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, E}^2 + \sum_{E \in \mathcal{E}_F} h_E \| \mathbf{v}_E - \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, E}^2.
\]

(3.31)

The consistency property (3.20) allows us to write:

\[
\| \mathbf{v}_{\gamma,F} \|_{\nabla, F}^2 + \| \mathbf{v}_{\gamma,F} \|_{\nabla, F}^2 = \| \pi_{\gamma,F}^k \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, F}^2 + \| \pi_{\gamma,F}^k \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, F}^2 \leq 2 \| \gamma_{\nabla,F}^{k+1} \mathbf{v}_F \|_{\nabla, F}^2 \lesssim \| \mathbf{v}_F \|_{\nabla, F}^2.
\]

(3.32)

We conclude by combining (3.31) and (3.32) to show that

\[
\| \mathbf{v}_F \|_{\nabla, F}^2 \lesssim \| \mathbf{v}_F \|_{\nabla, F}^2.
\]

Lemma 15. It holds, for all \( F \in \mathcal{F}_h \) and all \( \mathbf{W}_F \in \chi^{k+1}_{L^2,F} \),

\[
\forall \mathbf{W}_F \in \chi^{k+1}_{L^2,F}, \| \mathbf{W}_F \|_{L^2,F} \approx \| \mathbf{W}_F \|_{L^2,F}.
\]

Proof. The same proof as Lemma 14 works.

4 Complex property.

In this section we regard the following sequence:

\[
\chi^k_{\mathrm{rot},h} \xrightarrow{C^k_h} \chi^k_{\nabla,h} \xrightarrow{D^k} \chi^{k}_{L^2,h}.
\]

(4.1)

We will show in Theorem 17 that (4.1) is indeed a complex, but first we show that the interpolators form a cochain morphism from a continuous de Rham complex into the sequence (4.1).

Lemma 16 (Local commutation properties). It holds for all \( F \in \mathcal{F}_h \),

\[
\begin{align*}
C^k_h(I^k_{\mathrm{rot},F} q) &= I^k_{\nabla,F} \mathrm{rot} \ q, \quad \forall q \in C^1(F), \\
\sum_{F}^{k+1}(I^k_{\nabla,F} v) &= I^{k+1}_{L^2(F)} \nabla \ v, \quad \forall v \in C^1(F), \\
D^k(I^k_{\nabla,F} v) &= \pi^k_{P,F} \, \text{div} \ v, \quad \forall v \in C^0(F) \cap H^1(F).
\end{align*}
\]

(4.2a-b-c)

Proof. Proof of (4.2a). Let \( q \in C^1(F) \) and \( g_F = I^k_{\mathrm{rot},F} q \). We set \( \mathbf{v}_F = C^k_h g_F \), and we see that for all \( E \in \mathcal{F}_E \) of vertices with coordinates \( x_{V_1} \) and \( x_{V_2} \), for all \( r \in \mathcal{P}^k(E) \),

\[
\int_E q'_E r = - \int_E q_E r' + q_E(x_{V_1}) r(x_{V_1}) - q_E(x_{V_2}) r(x_{V_2})
\]

\[
= - \int_E q r' + q(x_{V_1}) r(x_{V_1}) - q(x_{V_2}) r(x_{V_2})
\]

\[
= \int_E q' r.
\]

We used the continuity of \( p_E \) and the fact that \( r' \in \mathcal{P}^{k-1}(F) \) thus:

\[
\pi^k_{P,E}(\mathbf{v}_E \cdot (-n_E)) = q'_E = \pi^k_{P,E}(\text{grad} \ q \cdot t_E) = \pi^k_{P,E}(\text{rot} \ q \cdot (-n_E)).
\]
Moreover, by definition $\pi^k_{P,E}(v \cdot t_E) = \pi^k_{P,E}(\text{rot } q \cdot t_E)$, $v_E(x_V) = \text{rot } q(x_V)$. and for all $r_F \in \mathcal{N}^k(F)$, using (2.10) we see that:

$$\int_F v_F \cdot r_F = \int_F q_F \text{rot } r_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E q_{r_F} \cdot t_E$$

$$= \int_F q \text{rot } r_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E q_{r_F} \cdot t_E$$

$$= \int_F \text{rot } q \cdot r_F.$$

Proof of (4.2b). Immediate consequence of (3.16) and (3.17).

Proof of (4.2c). Let $v \in C^0(F) \cap H^1(F)$, we set $v_F = \mathbf{I}_{\mathcal{V},F} v$ and $q_F = D^h_F v_F$. For all $w_F \in \mathcal{P}^k(F)$, since $\text{grad } w_F \in \mathcal{G}^{k-1}(F)$ we have:

$$\int_F q_{F} w_F = - \int_F v_{\mathcal{Q},F} \text{grad } w_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_{E} \cdot n_{E} w_F$$

$$= - \int_F v \text{grad } w_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v \cdot n_{E} w_F$$

$$= \int_F \text{div } w_F.$$

\[\square\]

**Theorem 17** (Complex property). It holds:

$$J^k_{\text{rot, } h} \mathbb{R} = \text{Ker } C^k_h,$$

(4.3a)

$$\text{Im } C^k_h \subset \text{Ker } D^h_h,$$

(4.3b)

$$\text{Im } D^h_h = \mathcal{P}^{k}(F).$$

(4.3c)

**Proof.** Proof of (4.3a). The inclusion $J^k_{\text{rot, } h} \mathbb{R} \subset \text{Ker } C^k_h$ is immediate since for all $F \in \mathcal{F}_h$ and all $r_F \in \mathcal{P}^k(F)$, the continuous integration by parts gives

$$\int_F \text{rot } r_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E r_F \cdot t_E = 0.$$ Conversely if $q^F_{h} \in \mathcal{X}^k_{\text{rot, } h}$ is such that $C^k_h q^F_{h} = 0$ then for all $E \in \mathcal{E}_h$, $R^q_{q,E} = 0$ and for all vertex $V \in \mathcal{V}_h$, $R^q_{q,V} = 0$. Moreover $q^F_{E} = 0$ so $q^F_{E}$ is constant on each edge and since it is continuous on vertices and $\Omega$ has a single connected component there is $C \in \mathbb{R}$ such that $\forall E \in \mathcal{E}_h$, $q^F_{E} = C$. By (3.11) and (3.10) we must have for all $F \in \mathcal{F}_h$, $\forall r_F \in \mathcal{N}^k(F)$, $\int_F q_{F} \text{rot } r_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E q_{r_F} \cdot t_E = 0$. Substituting $q^F_{E}$ by $C$ and doing an integration by parts we get $\int_F (q_{F} - C) \text{rot } r_F = 0$. We can conclude that $q_{F} = C$ since $\text{rot } \mathcal{N}^k(F) \rightarrow \mathcal{P}^{k-1}(F)$ is onto.

Proof of (4.3b). Let $p^F_{h} \in \mathcal{X}^k_{\text{rot, } h}$ and $v_F = C^k_{h} p^F_{h}$. For all $F \in \mathcal{F}_h$ and all $w_F \in \mathcal{P}^k(F)$ we have:

$$\int_E v_{E} \cdot n_{E} w_F = \int_E \pi^k_{P,E} v_{E} \cdot n_{E} w_F = - \int_E q^F_{E} w_F.$$ If we write $x_{E_1}$ and $x_{E_2}$ the coordinates of the vertices of the edge $E$, we have

$$- \int_E q^F_{E} w_F = \int_E q^F_{E} w'_F - q_{E} w_F(x_{E_1}) + q_{E} w_F(x_{E_2}).$$

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where \( w_F' \) is the derivative along \( E \) so \( w_F' = \text{grad} \ w_F \cdot t_E \). Moreover,
\[
\sum_{E \in \mathcal{E}_F} \omega_{FE}(x_{E2}) - q_E w_F(x_{E1}) = 0 \quad \text{thanks to the continuity of } q_E \text{ so:}
\]
\[
\sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E \cdot n_E w_F = \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E q_E \text{grad} w_F \cdot t_E. \tag{4.4}
\]

On the other hand we have:
\[
- \int_F v_G \cdot \text{grad} w_F = - \int_F q_F \text{rot} \text{grad} w_F - \sum_{E \in \mathcal{F}_E} \omega_{FE} \int_E q_E \text{grad} w_F \cdot t_E = - \sum_{E \in \mathcal{F}_E} \omega_{FE} \int_E q_E \text{grad} w_F \cdot t_E.
\]
Summing with (4.4) we find \( D^k_F v_F = 0 \), for all \( F \in \mathcal{F}_h \).

Proof of (4.3c) See Lemma 24.

The complex is exact if and only is the inclusion (4.3b) is in fact an equality. We can show that this the same as asking for \( \Omega \) to be contractible. The proof is a slight adaptation of [9, Section 4.3], and will not be duplicated here.

5 Consistency results.

The last things we need to show in order to efficiently use this complex are consistency results. First we show primal consistency results, controlling the error made when we use the interpolators. Then we show some Poincaré type results useful to show stability, including a discrete counterpart to the right inverse for the divergence Lemma 24. Finally we show adjoint consistency results, which control the error made when we perform a discrete integration by parts.

We begin by recalling a result from [1, Lemma 4.3.4]: \( \forall p \in (1, \infty), \forall q \in \mathbb{N} \text{ such that } pq > 2, \forall w \in W^{q,p}(F), \)
\[
\|w\|_{C^1(F)} \lesssim h^{2} F \sum_{r=0}^{q} h^r_F |w|_{W^{r,p}(F)}. \tag{5.1}
\]

Lemma 18 (Primal consistency). For all \( F \in \mathcal{F}_h \), it holds:
\[
\|
\gamma_{\nabla,F}^{k+1}(I_{\nabla,F}^k v) - v \| \lesssim h^{k+1} |v|_{H^{k+2}}, \quad \forall v \in H^{k+2}(F). \tag{5.2}
\]

Proof. For all \( F \in \mathcal{F}_h, (3.19) \) shows that \( \gamma_{\nabla,F}^{k+1}(I_{\nabla,F}^k v) \| \lesssim \|v\| + h \|v\|_{H^1} + h^2 \|v\|_{H^2} \) to conclude with the lemma on approximation properties of bounded projector [10, Lemma 1.43]. And starting from (3.30) we have
\[
\|
\gamma_{\nabla,F}^{k+1}(I_{\nabla,F}^k v) \| \lesssim \|I_{\nabla,F}^k v\|_{\nabla,F} \]
\[
\lesssim \|\pi_{\nabla,F}^{k} v\|_{F} + \|\pi_{\nabla,F}^{k-1} v\|_{F} + \sum_{E \in \mathcal{E}_F} h^{2}_E \|\pi_{\nabla,F}^{k+2} v\|_{E} \]
\[
\lesssim \|v\|_{F} + h_{F} |v|_{H^1(F)},
\]
where we used the continuous trace inequality [10, Lemma 1.31] and the boundedness of \( L^2 \) projectors.
Lemma 19 (Stabilization forms consistency). For all $F \in \mathcal{F}_h$ it holds:

$$s_{\nabla,F} \left( \mathbf{I}^{k}_{\nabla,F} \mathbf{v}, \mathbf{I}^{k}_{\nabla,F} \mathbf{v} \right) ^{1/2} \lesssim h^{k+2} | \mathbf{v} |_{H^{k+2}(F)}, \forall \mathbf{v} \in H^{k+2}(F). \tag{5.3}$$

$$s_{L^2,F} \left( \mathbf{I}^{k}_{L^2(F)} \mathbf{W}, \mathbf{I}^{k}_{L^2(F)} \mathbf{W} \right) ^{1/2} \lesssim h^{k+1} | \mathbf{W} |_{H^{k+1}(F)}, \forall \mathbf{W} \in H^{k+1}(F) \cap C^0(\overline{F}). \tag{5.4}$$

Proof. Proof of (5.3). For all $z_F \in \mathcal{P}^{k+1}(F)$ we have $\gamma^{k+1}_{\nabla,F}(\mathbf{I}^{k}_{\nabla,F} z_F) = z_F$ by (3.19) so for all $\mathbf{w}_F \in X^{k}_{\nabla,F}$,

$$s_{\nabla,F} \left( \mathbf{I}^{k}_{\nabla,F} z_F, \mathbf{w}_F \right) = \sum_{E \in \mathcal{E}_F} h_E \left( \gamma^{k+1}_{\nabla,F}(\mathbf{I}^{k}_{\nabla,F} z_F) \cdot (\gamma^{k+1}_{\nabla,F} \mathbf{w}_F - \mathbf{w}_F) \right) = 0.$$

Hence

$$s_{\nabla,F} \left( \mathbf{I}^{k}_{\nabla,F} \mathbf{v}_F, \mathbf{I}^{k}_{\nabla,F} \mathbf{v}_F \right) = s_{\nabla,F} \left( \mathbf{I}^{k}_{\nabla,F} (\mathbf{v}_F - \pi^{k+1}_{\mathcal{P},F}), \mathbf{I}^{k}_{\nabla,F} (\mathbf{v}_F - \pi^{k+1}_{\mathcal{P},F}) \right) \lesssim \| \mathbf{I}^{k}_{\nabla,F} (\mathbf{v}_F - \pi^{k+1}_{\mathcal{P},F}) \|^{2}_{\nu,F}.$$

We conclude by the norm equivalence Lemma [14, Theorem 1.45]. Proof of (5.4). Let $\mathbf{W} \in H^{k+1}(F) \cap C^0(F)$, we have:

$$s_{L^2,F} \left( \mathbf{I}^{k}_{L^2(F)} \mathbf{W}, \mathbf{I}^{k}_{L^2(F)} \mathbf{W} \right) = \sum_{E \in \mathcal{E}_F} h_E \| \pi^{k+1}_{\mathcal{P},E} \mathbf{W} \cdot \mathbf{t}_E - \pi^{k+1}_{\mathcal{P}^*,F} \mathbf{W} \cdot \mathbf{t}_E \|^{2}_{E}$$

$$\leq \sum_{E \in \mathcal{E}_F} h_E \| \mathbf{W} - \pi^{k+1}_{\mathcal{P}^*,F} \mathbf{W} \|^{2}_{E}$$

$$\leq \sum_{E \in \mathcal{E}_F} h_E \left( \| \mathbf{W} - \pi^{k}_{\mathcal{P},F} \mathbf{W} \|^{2}_{E} + \| \pi^{k}_{\mathcal{P},F} \mathbf{W} - \pi^{k+1}_{\mathcal{P}^*,F} \mathbf{W} \|^{2}_{E} \right)$$

$$\lesssim h^{2(k+1)} | \mathbf{W} |_{H^{k+1}} + \| \mathbf{W} - \pi^{k}_{\mathcal{P},F} \mathbf{W} \|^{2}_{F}.$$

Here the second equality comes from $\overline{\mathcal{R}T}^{k+1}(F) \cdot \mathbf{t}_E \subset (\mathcal{P}^{k+1}(E))^2$ and we used the approximation properties on traces [10, Theorem 1.45 and Equation 1.75] on the first term and the discrete trace inequality [10, Lemma 1.32] on the second term to get the last equality. We conclude with [10, Theorem 1.45 and Equation 1.74].

5.1 Poincaré inequality.

We begin by stating two lemmas which will be useful to prove the Poincare inequality.

Lemma 20. For all $F \in \mathcal{F}_h$ and all $\mathbf{v}_F \in X^{k}_{\nabla,F}$ it holds that

$$\sum_{E \in \mathcal{E}_F} h^{-1}_E \| \gamma^{k+1}_{\nabla,F} \mathbf{v}_F - \mathbf{v}_E \|^{2}_{E} \lesssim \| \sum^{k+1}_{\nu,F} \mathbf{v}_F \|^{2}_{L^2,F}. \tag{5.5}$$

Proof. The proof is a simple adaptation of [14, Lemma 35].

Lemma 21. For all $F \in \mathcal{F}_h$ and all $\mathbf{v}_F \in X^{k}_{\nabla,F}$ it holds that

$$\| \nabla \gamma^{k+1}_{\nabla,F} \mathbf{v}_F \|^{2} + \sum_{E \in \mathcal{E}_F} h^{-1}_E \| \gamma^{k+1}_{\nabla,F} \mathbf{v}_F - \mathbf{v}_E \|^{2}_{E} \lesssim \| \sum^{k+1}_{\nu,F} \mathbf{v}_F \|^{2}_{L^2,F}. \tag{5.6}$$
Proof. Let $W_F = \nabla \gamma_{\nabla F}^{k+1} u_F$, we have
\[
\| \nabla \gamma_{\nabla F}^{k+1} u_F \| = - \int_F \gamma_{\nabla F}^{k+1} u_F \cdot \nabla W_F + \sum_{E \in \mathcal{F}_F} \omega_{FE} \int_E \gamma_{\nabla F}^{k+1} u_F W_F n_E
\]
\[
= \int_F \nabla \gamma_{\nabla F}^{k+1} u_F : W_F + \sum_{E \in \mathcal{F}_F} \omega_{FE} \int_E (\gamma_{\nabla F}^{k+1} u_F - v_E) W_F n_E
\]
\[
\leq \| \nabla \gamma_{\nabla F}^{k+1} u_F \| \| W_F \| + \sum_{E \in \mathcal{F}_F} \omega_{FE} \| \gamma_{\nabla F}^{k+1} u_F - v_E \| E h^\frac{1}{2} \| W_F \|_E
\]
\[
\lesssim \| \nabla \gamma_{\nabla F}^{k+1} u_F \| \| W_F \| + \| W_F \| \sum_{E \in \mathcal{F}_F} \omega_{FE} \| \gamma_{\nabla F}^{k+1} u_F - v_E \| (E h^\frac{1}{2})^\frac{1}{2}
\]
\[
\lesssim \| \nabla \gamma_{\nabla F}^{k+1} u_F \| \| W_F \|.
\]
We used $W_F \in (P_k(F))^2$ with Remark 10 on the second line, the discrete trace inequality Lemma 3 on the third, and we concluded with Lemma 20. \qed

Lemma 22. For all $v_h \in X^k_{\nabla h}$ such that $\sum_{F \in \mathcal{F}_h} \int_F \nabla_{\nabla F}^{k+1} u_F = 0$ it holds that
\[
\| v_h \|_{\nabla h} \lesssim \| \nabla_{\nabla F}^{k+1} u_h \|_{L^2,h}.
\]
Proof. The proof is a simple adaptation of [14, Theorem 31]. \qed

Remark 23. When $k \geq 1$ the assumption $\sum_{F \in \mathcal{F}_h} \int_F \nabla_{\nabla F}^{k+1} u_F = 0$ translates to $\sum_{F \in \mathcal{F}_h} \int_F v_F = 0$ by (3.20). However this does not hold when $k = 0$.

Lastly we show that the fully discrete divergence is onto $D^k_h : X^k_{\nabla,h} \to X^k_{L^2,h}$. The main difficulty is to show the boundedness of the inverse with the discrete norms.

Lemma 24 (Right-inverse for the divergence). For all $p_h \in X^k_{L^2,h}$ there is $v_h \in X^k_{\nabla,h}$ such that $D^k_h v_h = p_h$ and $\| v_h \|_{\nabla h} + \| \nabla_{\nabla F}^{k+1} u_h \|_{L^2,h} \lesssim \| p_h \|_{L^2,h}$.

Proof. Existence. Let $p_h = (p_F)_{F \in \mathcal{F}_h} \in X^k_{L^2,h}$ and apply Lemma 40 to find $\tilde{p} \in C^0(\Omega)$ such that $\forall F \in \mathcal{F}_h$, $\tilde{p}_F \in P_{k+\max_{h,E \in \mathcal{E}_h}}(|E F|)(F)$, $\pi_{P,F} \tilde{p} = p_F$ and $\| \tilde{p} \|_{L^2, \mathcal{E}} \approx \| p_h \|_{L^2,h}$. Under the assumption on the regularity of the mesh we have $\max_{h,E \in \mathcal{E}_h}(|E F|) \approx 1$ (10, Lemma 1.12) so that the maximum degree is bounded independently of $h$. Since $\tilde{p}$ is a piecewise polynomial, continuous and of trace zero on the boundary, $\tilde{p} \in H^1_0(\Omega)$. We apply Theorem 13 to find $u \in H^2(\Omega)$ such that $\nabla u = \tilde{p}$, $\| u \|_{H^2} \lesssim \| \tilde{p} \|_{H^1}$ and $\| u \|_{H^1} \lesssim \| \tilde{p} \|_{L^2}$. We build $v_h \in X^k_{\nabla,h}$ in such a way that on each edge $E \in \mathcal{E}_h$, $\pi_{\nabla F} \nabla_{\nabla}^k v_E = \pi_{\nabla F}^k u$ and on each vertex $V \in \mathcal{V}_h$ of coordinate $x_V$, $v_E(x_V) = 0$.

Then on each face $F \in \mathcal{F}_h$ since $\text{grad} : P^{0,k}(F) \to G^{k-1}(F)$ is an isomorphism, we can choose $v_{\nabla,F} u$ such that $\forall w_F \in P^{0,k}(F),$
\[
- \int_F v_{\nabla,F} \nabla w_F + \sum_{E \in \mathcal{F}_E} \omega_{FE} \int_E v_E \cdot n_{EF} w_F = \int_F p_F w_F.
\]
Finally we set $v_{\nabla,F} = \pi_{\nabla F}^k u$ so that $\forall w_F \in P^{0,k}(F)$, $\int_F D^k_h v_F w_F = \int_F p_F w_F$ and $\forall w_F \in P^{0}(F)$,
\[
\int_F D^k_h v_F w_F = \sum_{E \in \mathcal{F}_E} \omega_{FE} \int_E v_E \cdot n_{EF} w_E = \int_E u \cdot n_E
\]
\[
= w_F \int_F \nabla u = w_F \int_F \tilde{p} = \int_F w_F \tilde{p}.
\]
The second equality comes from \( \forall E \in \mathcal{E}_h, \pi_{P,E}^0v_E = \pi_{P,E}^0u \) and the last equality from \( \forall F \in \mathcal{F}_h, \pi_{P,F}^0p = \pi_{P,F}^0p_F \). Thus we have \( D_h^Fv_h = p_h \).

**Boundedness.** It remains to show that \( \|v_h\|_{\mathcal{V},h} \lesssim \|p_h\|_{L^2,h} \). For any face \( F \in \mathcal{F}_h \) remind that

\[
\|v_F\|_{\mathcal{V},F}^2 = \|v_{g,F}\|_{F}^2 + \|v_{g,F}^c\|_{F}^2 + \sum_{E \in \mathcal{E}_F} h_E\|v_E\|_{E}^2. \tag{5.8}
\]

We estimate the last term of (5.8) with:

\[
\|v_E\|_{E} \approx \|\pi_{P,E}^k v_E\|_{E} = \|\pi_{P,E}^k u\|_{E} \lesssim \|u\|_{E},
\]

where the first equality comes from Lemma \[10\] applied in one dimension. The continuous trace inequality \[10\] Lemma 1.31] gives

\[
h_F^{1/2}\|u\|_{E} \lesssim \|u\|_{L^2(F)} + h_F\|u\|_{H^1(F)} \lesssim \|u\|_{H^1(F)}.
\]

To estimate the first term of (5.8) we take \( w_F \in P^{0,k}(F) \) such that \( \text{grad } w_F = v_{g,F} \) so \( w_F \| \lesssim h_F\|v_{g,F}\| \) and by construction:

\[
\int_F v_{g,F} \cdot v_{g,F} = -\int_F p_F w_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E \cdot n_E w_F
\]

\[
\leq \|p_F\|_F\|w_F\|_F + \sum_{E \in \mathcal{E}_F} h_E^{-1}h_F^{1/2}\|v_E\|_{E}h_F^{1/2}\|w_F\|_E
\]

\[
\lesssim \|p_F\|_F\|w_F\|_F + h_F^{-1}\|w_F\|_F \sum_{E \in \mathcal{E}_F} h_F^{1/2}\|v_E\|_E
\]

\[
\lesssim \|v_{g,F}\|_F(\|p_F\|_F + \sum_{E \in \mathcal{E}_F} h_F^{1/2}\|v_E\|_E).
\]

Applying the same estimate on the boundary we find

\[
\|v_{g,F}\|_F^2 \lesssim \|p_F\|_F^2 + \|u\|_{H^1(F)}^2.
\]

Lastly for the middle term of (5.8):

\[
\|v_{g,F}^c\|_F = \|\pi_{P,F}^{c,k} u\|_F \leq \|u\|_{L^2(F)} \leq \|u\|_{H^1(F)},
\]

hence, summing over every face \( F \in \mathcal{F}_h \) gives

\[
\|v_h\|_{\mathcal{V},h}^2 \lesssim \|p_h\|_{L^2,h}^2 + \|u\|_{H^1(\Omega)}^2 \lesssim \|p_h\|_{L^2,h}^2.
\]

Now to estimate \( \left\|\sum_{h}^{k+1} v_h\right\|_{L^2,h} \) let \( W_F = \nabla E_{\mathcal{F}}^+ v \) and \( q_F \in P^{0,k}(F) \) such that \( \nabla \cdot W_{\mathcal{F},F} = \text{grad } q_F \) and \( \|q_F\| \approx \|W_{\mathcal{F},F}\| \). We have:

\[
\int_F \nabla E_{\mathcal{F}}^+ v_F \cdot \nabla E_{\mathcal{F}}^+ v_F = -\int_F v_{g,F} \cdot \nabla W_{\mathcal{F},F} - \int_F v_{g,F} \cdot \nabla W_{\mathcal{F},F} + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E W_F \cdot n_E
\]

\[
= -\int_F v_{g,F} \cdot \nabla W_{\mathcal{F},F} + \int_F p_F q_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E (W_F - q_F I_{2,2}) \cdot n_E.
\]

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Applying (2.10) gives
\[
\int_E v_E (W_F - q_F I_{2,2}) \cdot n_E = \int_E \pi_{F,E} v_E (W_F - q_F I_{2,2}) \cdot n_E = \int_E u (W_F - q_F I_{2,2}) \cdot n_E
\]
so that after an integration by parts:
\[
\sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E (W_F - q_F I_{2,2}) \cdot n_E = \int_E \nabla u : (W_F - q_F I_{2,2}) + \int_E u \cdot \nabla (W_F - q_F I_{2,2}).
\]
Since \( \nabla \cdot (W_F - q_F I_{2,2}) = \nabla \cdot W^c_{\mathcal{F},F} \) by (2.15) we have:
\[
\int_F \nabla^{k+1} \varphi_F : \nabla^{k+1} \varphi_F = - \int_F \varphi_F v^c \cdot \nabla \cdot W^c_{\mathcal{F},F} + \int_F \nabla u : (W_F - q_F I_{2,2}) + \int_F u \cdot \nabla W^c_{\mathcal{F},F} = \int_F \nabla u : (W_F - q_F I_{2,2}),
\]
thus
\[
\| \nabla^{k+1} \varphi_F \|^2 \lesssim \| \nabla u \| \| \nabla^{k+1} \varphi_F \| F. \tag{5.9}
\]
Let us now focus on the estimate over edges. The Poincare-Wirtinger inequality and Lemma 2 show that for all polynomial \( r \) defined on \( E \in \mathcal{E}_h \), \( \| r - \frac{1}{|E|} \int_E r \| E \approx h^{-1} \| \nabla r \| E \). Since
\[
\| v_E - \frac{1}{|E|} \int_E v_E \|^2_E = \| v_E \|^2_E - \frac{1}{|E|} (\int_E v_E)^2, \| \pi_{F,E} v_E \|^2_E \approx \| v_E \| E \text{ and } \int_E v_E = \int_E \pi_{F,E} v_E \text{ we have } \| v'_E \| E \approx \| \pi_{F,E} v_E \| E,
\]
\[
\| v'_E \| E \approx \| \pi_{F,E} v_E \| E = \| \pi_{F,E} v_E - u' \| E \leq \| \pi_{F,E} u - u' \| E + \| \nabla u \| E.
\]
By Theorem 1.45 we see that \( h_E \| \pi_{F,E} u - u' \| E \lesssim \| u \|_{H^1(F)} \) and by the continuous trace inequality Lemma 1.31 that
\[
h_E \| \nabla u \| E \lesssim \| \nabla u \| + h_E \| \nabla u \| F,
\]
so
\[
h_E \| v'_E \|^2_E \lesssim \| u \|_{H^1(F)}^2 + h^2 \| u \|_{H^2(F)}^2. \tag{5.10}
\]
Combining (5.9), (5.10) and summing over every face we get:
\[
\left\| \left[ \sum_{k=1}^{k+1} v_h \right] \right\|_{L^2,h}^2 \lesssim \| u \|_{H^1(\Omega)}^2 + h^2 \| u \|_{H^2(\Omega)}^2.
\]
We can conclude since \( \| u \|_{H^1(\Omega)} \lesssim \| P_h u \|_{L^2,h} \) and
\[
h \| u \|_{H^2(\Omega)} \lesssim h \| \hat{p} \|_{H^1(\Omega)} \lesssim \| \hat{p} \|_{L^2(\Omega)} \lesssim \| P_h \|_{L^2,h},
\]
where we used the inverse Poincare inequality on \( h^2 \| \hat{p} \|_{H^1(\Omega)}^2 = \sum_{F \in \mathcal{F}_h} h^2 \| \hat{p} \|_{H^1(F)}^2. \)

Remark 25. We can easily adapt Lemma 24 to require \( \sum_{F \in \mathcal{F}_h} \int_F \gamma_{\mathcal{F},F}^{k+1} v'_F = 0 \). Simply define \( v'_h = v_h - \sum_{F \in \mathcal{F}_h} \int_F \gamma_{\mathcal{F},F}^{k+1} v'_F \). It is clear from (3.19) that \( \sum_{F \in \mathcal{F}_h} \int_F \gamma_{\mathcal{F},F}^{k+1} v'_F = 0 \), from Lemma 16 that \( \mathcal{D}_h v'_h = P_h \) and from (3.30) that the estimate of Lemma 24 on the norm of \( v'_h \) still holds.
5.2 Adjoint consistency.

We define the adjoint consistency error for all \( W \in C^0(\Omega) \cap H^1_0(\Omega) \) and all \( \psi_h \in X_h^k \) by:

\[
\tilde{\mathcal{E}}_{\nabla,h}(W, \psi_h) = \sum_{F \in \mathcal{F}_h} \left( (I_{L^2(F)}^k W, \nabla_{F}^{k+1} \psi_F)_{L^2,F} + \int_F \nabla \cdot W \cdot \gamma_{\nabla,h}^{k+1} \psi_F \right). \tag{5.11}
\]

**Theorem 26** (Adjoint consistency for the gradient). For all \( W \in C^0(\Omega) \cap H^1_0(\Omega) \) such that \( W \in H^{k+2}(\mathcal{F}_h) \) and all \( \psi_h \in X_h^k \),

\[
|\tilde{\mathcal{E}}_{\nabla,h}(W, \psi_h)| \lesssim h^{k+1} \left( |W|_{H^{k+1}} + |W|_{H^{k+2}} \right) \left( \|\psi_h\|_{\nabla,h} + \left\| \nabla_{\nabla,F}^{k+1} \psi_F \right\|_{L^2,h} \right). \tag{5.12}
\]

**Proof.** Remarks \[ and \[ show that \( \forall \phi_h \in (\mathcal{RT}^{k+1}(\mathcal{F}_h))^2 \),

\[
\int_F \gamma_{\nabla,F}^{k+1} \psi_F \cdot \nabla \cdot W_F + \int_F \nabla_{F}^{k+1} \psi_F : W_F - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E W_F n_E = 0.
\]

Moreover, since \( W \cdot n_\Omega = 0 \) on \( \partial \Omega \) and since the \( v_F \) are single valued we have

\[
\sum_{F \in \mathcal{F}_h} \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E W n_E = 0. \tag{5.13}
\]

Hence we can write:

\[
\tilde{\mathcal{E}}_{\nabla,h}(W, \psi_h) = \sum_{F \in \mathcal{F}_h} \left( \int_F (W - W_F) : \nabla_{F}^{k+1} \psi_F + \int_F \nabla \cdot (W - W_F) \cdot \gamma_{\nabla,F}^{k+1} \psi_F \right)
\]

\[
+ \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E (W_F - W) n_E + s_{L^2,F} \left( I_{L^2(F)}^k W, \nabla_{F}^{k+1} \psi_F \right)
\]

\[
\lesssim \sum_{F \in \mathcal{F}_h} \left( \|W - W_F\| + \| \nabla \cdot (W - W_F)\| \right) \left( \| \nabla_{F}^{k+1} \psi_F\| + \| \gamma_{\nabla,F}^{k+1} \psi_F\| \right)
\]

\[
+ s_{L^2,F} \left( I_{L^2(F)}^k W, I_{L^2(F)}^k W \right)^{1/2} s_{L^2,F} \left( \nabla_{F}^{k+1} \psi_F, \nabla_{F}^{k+1} \psi_F \right)^{1/2}
\]

\[
+ \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E (W - W_F) n_E.
\]

Applying (5.4) and Lemma \[ gives:

\[
s_{L^2,F} \left( I_{L^2(F)}^k W, I_{L^2(F)}^k W \right)^{1/2} \lesssim h^{k+1} \left( |W|_{H^{k+1}(F)} + |W|_{H^{k+2}(F)} \right).
\]

Using the approximation properties of the spaces \( \mathcal{RT}^{k+1}(F) \) given by a slight adaptation of \[ Lemma 43 \] we can find \( W_F \in (\mathcal{RT}^{k+1}(\mathcal{F}_h))^2 \) such that

\[
\|W - W_F\| + \| \nabla \cdot (W - W_F)\| \lesssim h^{k+1} \left( |W|_{H^{k+1}(F)} + |W|_{H^{k+2}(F)} \right)
\]

By \[ we see that

\[
\| \nabla_{F}^{k+1} \psi_F\| + \| \gamma_{\nabla,F}^{k+1} \psi_F\| \lesssim \left\| \nabla_{F}^{k+1} \psi_F\right\|_{L^2,F} + \| \psi_F\|_{\nabla,F}.
\]
Lastly we use Theorem 28 to find \( R_{\nabla F} \in H^1(F) \) such that
\[
\sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E (W - W_F) n_E = \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E R_{\nabla F} (W - W_F) n_E
= \int_F \nabla R_{\nabla F} : (W - W_F) + \int_F R_{\nabla F} \cdot \nabla (W - W_F).
\]

Hence
\[
\sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E (W - W_F) n_E \lesssim (\|W - W_F\| + \|\nabla (W - W_F)\|) (\|\nabla R_{\nabla F}\| + \|R_{\nabla F}\|)
\]
and we conclude with Theorem 41 which gives the boundedness of \( R_{\nabla F} \).

We can sharpen the estimate (5.11) when \( W \) is the gradient of some field. Indeed, if were to take \( W = \nabla w \) in Theorem 26 we would see that a norm over \( H^{k+2} \) appears in the estimate, which is suboptimal.

We define the adjoint consistency error for all \( w \in H^2(\Omega) \) such that \( \nabla w \cdot n_\Omega = 0 \) and all \( v_h \in X_{V,F}^k \) by:
\[
\tilde{e}_{\Delta,h}(w, v_h) = \sum_{F \in \mathcal{F}_h} \left( \int_F \nabla \cdot \gamma_{V,F}^{k+1} w_F + \left( \nabla \gamma_{V,F}^{k+1} w_F, \nabla \gamma_{V,F}^{k+1} v_F \right)_{L^2(F)} \right).
\]
(5.14)

Remark 27. The assumption \( w \in H^2(\Omega) \) imply that \( w \in C^0(\overline{\Omega}) \) in two dimensions (see e.g. [2], pp. 12.60).

Theorem 28 (Adjoint consistency for the Laplacian). For all \( w \in H^2(\Omega) \) such that \( \nabla w \cdot n_\Omega = 0 \) and \( w \in H^{k+2}(\mathcal{F}_h) \) and for all \( v_h \in X_{V,F}^k \),
\[
|\tilde{e}_{\Delta,h}(w, v_h)| \lesssim h^{k+1} |w|_{H^{k+2}} \left\| \nabla \gamma_{V,F}^{k+1} v_h \right\|_{L^2,F}.
\]
(5.15)

Proof. For any \( F \in \mathcal{F}_h \), (4.2b) gives:
\[
\left( \nabla \gamma_{V,F}^{k+1} w_F, \nabla \gamma_{V,F}^{k+1} v_F \right)_{L^2,F} = \int_F \nabla \gamma_{V,F}^{k+1} w_F \cdot \nabla \gamma_{V,F}^{k+1} v_F + s_{L^2,F} \left( L^k_{L^2}(F) \nabla w, \nabla \gamma_{V,F}^{k+1} v_F \right).
\]
With an integration by parts and since \( \int_F \nabla \gamma_{V,F}^{k+1} w_F \cdot \nabla \gamma_{V,F}^{k+1} v_F = \int_F \nabla w : \nabla \gamma_{V,F}^{k+1} v_F \) we have:
\[
\tilde{e}_{\Delta,h}(w, v_h) = \sum_{F \in \mathcal{F}_h} \left( \int_F \nabla w : (\nabla \gamma_{V,F}^{k+1} v_F - \nabla \gamma_{V,F}^{k+1} v_F) + s_{L^2,F} \left( L^k_{L^2}(F) \nabla w, \nabla \gamma_{V,F}^{k+1} v_F \right) + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \nabla \gamma_{V,F}^{k+1} v_F \nabla n_E \right)
\]
Since we assume \( \nabla w \cdot n_\Omega = 0 \) we have
\[
\sum_{F \in \mathcal{F}_h} \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E v_E \nabla w = 0
\]
(5.16)
so by Remark 10 it holds $\forall w_F \in \mathcal{P}^{k+1}(F)$,

$$\int_F \Delta w_F \cdot \gamma^{k+1}_{\nabla, F} v_F + \int_F \nabla^{k+1}_{F} v_F : \nabla w_F - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E (w_E \nabla W) n_E = 0,$$

so

$$\int_F \nabla w_F : (\nabla^{k+1}_{F} v_F - \nabla \gamma^{k+1}_{\nabla, F} v_F) + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E (\gamma^{k+1}_{\nabla, F} v_F - v_E) \nabla w_F n_E = 0.$$

This allows us to write for any $w_h = (w_F)_{F \in \mathcal{F}_h} \in \mathcal{P}^{k+1}(F)$,

$$\tilde{\mathcal{E}}_{\Delta, h}(w, v_h) = \sum_{F \in \mathcal{F}_h} \left( \int_F \nabla (w - w_F) : (\nabla^{k+1}_{F} v_F - \nabla \gamma^{k+1}_{\nabla, F} v_F) + s_{L^2, F} \left( \mathcal{I}^k_{L^2(F)} \nabla w, \nabla^{k+1}_{F} v \right) \right)$$

$$+ \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E (\gamma^{k+1}_{\nabla, F} v_F - v_E) \nabla (w - w_F) n_E,$$

$$|\tilde{\mathcal{E}}_{\Delta, h}(w, v_h)| \lesssim \sum_{F \in \mathcal{F}_h} \left( ||\nabla (w - w_F)||_{F} ||\nabla^{k+1}_{F} v_F - \nabla \gamma^{k+1}_{\nabla, F} v_F||_{F} \right)$$

$$+ \sum_{E \in \mathcal{E}_F} ||\gamma^{k+1}_{\nabla, F} v_F - v_E||_{E} ||\nabla (w - w_F)||_{E} + |s_{L^2, F} \left( \mathcal{I}^k_{L^2(F)} \nabla w, \nabla^{k+1}_{F} v \right)|_{E}.$$

Applying Lemma 20 we get

$$||\gamma^{k+1}_{\nabla, F} v_F - v_E||_{E} ||\nabla (w - w_F)||_{E} \lesssim ||\nabla^{k+1}_{F} v_F||_{L^2, F} h^{\frac{1}{2}} ||\nabla (w - w_F)||_{E}.$$

By (5.4) and Lemma 15 we get

$$|s_{L^2, F} \left( \mathcal{I}^k_{L^2(F)} \nabla w, \nabla^{k+1}_{F} v \right)| \lesssim h^{k+1} ||\nabla w||_{H^{k+1}(F)} ||\nabla^{k+1}_{F} v||_{L^2, F}.$$

Hence, applying Lemma 21 we write:

$$|\tilde{\mathcal{E}}_{\Delta, h}(w, v_h)| \lesssim \sum_{F \in \mathcal{F}_h} \left( ||\nabla^{k+1}_{F} v_F||_{L^2, F} (||\nabla (w - w_F)||_{F} + h^{\frac{1}{2}} ||\nabla (w - w_F)||_{E}) \right)$$

$$+ h^{k+1} ||w||_{H^{k+2}} ||\nabla^{k+1}_{F} v_F||_{L^2, F}.$$

We conclude by taking $w_F = \pi^{1,k+1}_{p,F} w$ the elliptic projection on $F$ (see [10, Definition 1.39]), then [10, Theorem 1.48] gives:

$$||w - \pi^{1,k+1}_{p,F} w||_{H^1(F)} \lesssim h^{k+1} ||w||_{H^{k+2}},$$

$$h^{\frac{1}{2}} ||w - \pi^{1,k+1}_{p,F} w||_{H^1(E)} \lesssim h^{k+1} ||w||_{H^{k+2}}.$$
6 Stokes equations.

Finally, we illustrate this complex with the resolution of the Stokes equations. For the sake of simplicity we use Neumann boundary conditions over the whole boundary, that it to say with a free outlet condition. More general conditions are not difficult to enforce and are discussed in Section 7. The solution is therefore determined only up to a constant vector field. The leads to the introduction of a new space:

$$X_{\nabla,h}^k := \{ v_h \in X_{\nabla,h}^k : \sum_{F \in \mathcal{F}_h} \int_F \gamma_{F,F}^{k+1} v_F = 0 \}. \quad (6.1)$$

This is the discrete counterpart of $L_0^2(\Omega)$.

Let $\mu$ be a constant viscosity, we define the symmetric bilinear form $a_h(v_h, w_h) \in X_{\nabla,h}^k \times X_{\nabla,h}^k \rightarrow \mathbb{R}$ on all $v_h, w_h \in X_{\nabla,h}^k$ by

$$a_h(v_h, w_h) := \mu \left( \sum_{h} v_h, \sum_{h} w_h \right)_{L^2,h}. \quad (6.2)$$

We also define the bilinear form $b_h(v_h, q_h) \in X_{\nabla,h}^k \times X_{L^2,h}^k \rightarrow \mathbb{R}$ on all $v_h \in X_{\nabla,h}^k, q_h \in X_{L^2,h}^k$ by

$$b_h(v_h, q_h) := \sum_{F \in \mathcal{F}_h} \int_{F} D_{F}X \cdot q_F. \quad (6.3)$$

Then we define the bilinear form $A_h((v_h, p_h), (w_h, q_h)) \in (X_{\nabla,h}^k, X_{L^2,h}^k) \times (X_{\nabla,h}^k, X_{L^2,h}^k) \rightarrow \mathbb{R}$ by

$$A_h((v_h, p_h), (w_h, q_h)) = a_h(v_h, w_h) - b_h(w_h, p_h) + b_h(v_h, q_h). \quad (6.4)$$

We define a suitable Sobolev-like norm on our discrete spaces such that $\forall v_h \in X_{\nabla,h}^k$,

$$\| v_h \|_{\mu, 1,h} := \left( \| v_h \|_{X_{\nabla,h}^k}^2 + a_h(v_h, v_h) \right)^{1/2}. \quad (6.5)$$

And for $f \in L^2(\Omega)$ we set $L_h : X_{\nabla,h}^k, \rightarrow \mathbb{R}$ such that $\forall v_h \in X_{\nabla,h}^k$,

$$L_h(v_h) := \sum_{F \in \mathcal{F}_h} \int_{F} \gamma_{F,F}^{k+1} v_F : f. \quad (6.6)$$

We define the discrete problem:

Find $(v_h, p_h) \in X_{\nabla,h}^k \times X_{L^2,h}^k$ such that for all $(w_h, q_h) \in X_{\nabla,h}^k \times X_{L^2,h}^k$

$$A_h((v_h, p_h), (w_h, q_h)) = L_h(v_h). \quad (6.7)$$

We show well-posedness in Lemma [30].

We consider the following Stokes problem:

Find $u \in H^2(\Omega) \cap L_0^2(\Omega), p \in H_0^1(\Omega)$ such that

$$-\mu \Delta u + \text{grad} p = f, \text{ on } \Omega,$$

$$\text{div} u = 0, \text{ on } \Omega,$$

$$\frac{\partial u}{\partial n_\Omega} = 0, \text{ on } \partial \Omega. \quad (6.8)$$

Let $(u, p)$ solves (6.8) and let $(v_h, p_h)$ solves (6.7). We assume that the continuous solutions $u, p$ have the additional smoothness $u \in H^{k+2}(\mathcal{F}_h)$ and $p \in H^{k+2}(\mathcal{F}_h)$. We deduce the following error estimate.
Theorem 29 (Error estimate for Stokes). Under the smoothness assumption on $u$ and $p$ it holds that
\[
\|w_h - I_k^{F,F}u\|_{\mu,\nabla,1,h} + \|p_h - \pi_h^{F,F}p\|_{L^2,F} \lesssim h^{k+1} \left( |u|_{H^{k+2}(F_h)} + |p|_{H^{k+1}(F_h)} + |p|_{H^{k+2}(F_h)} \right).
\] (6.9)

Proof. The proof is a direct application of the third Strang lemma (see [8]) to the estimates given by Lemma 30 and 31.  

Lemma 30 (Well-posedness.). For any $(w_h,p_h) \in X_{\nabla,1,h}^k \times X_{L^2,F}^k$ there is $(w_h',q_h') \in X_{\nabla,1,h}^k \times X_{L^2,F}^k$ such that
\[
A_h((w_h,p_h),(w_h',q_h')) \geq \|w_h\|_{\mu,\nabla,1,h}^2 + \|p_h\|_{L^2,F}^2.
\] (6.10)

Proof. Let $(w_h,p_h) \in X_{\nabla,1,h}^k \times X_{L^2,F}^k$, we have
\[
A_h((w_h,p_h),(w_h',q_h')) = a_h(w_h,w_h') + \|p_h\|_{L^2,F}^2
\geq -\frac{1}{2}\|w_h\|_{\mu,\nabla,1,h}^2 - \frac{1}{2}\|w_h'\|_{\mu,\nabla,1,h}^2 + \|p_h\|_{L^2,F}^2
\geq -\frac{1}{2}\|w_h\|_{\mu,\nabla,1,h}^2 + \frac{1}{2}\|p_h\|_{L^2,F}^2.
\] (6.11)

And we conclude by summing (6.10) and (6.11).  

We define the consistency error $E_h : X_{\nabla,1,h}^k \times X_{L^2,F}^k \to \mathbb{R}$ by
\[
E_h((w_h,q_h)) = L_h(w_h) - A_h((I_k^{F,F}u, \pi_h^{F,F}p), (w_h,q_h)).
\] (6.12)

Lemma 31. For all $w_h \in X_{\nabla,1,h}^k, q_h \in X_{L^2,F}^k$
\[
E_h((w_h,q_h)) \lesssim h^{k+1} \left( |u|_{H^{k+2}(F_h)} + |p|_{H^{k+1}(F_h)} + |p|_{H^{k+2}(F_h)} \right) \left( \|w_h\|_{\mu,\nabla,1,h} + \|p_h\|_{L^2,F} \right).
\]

Proof. Let $w_h \in X_{\nabla,1,h}^k, q_h \in X_{L^2,F}^k$
\[
E_h((w_h,q_h)) = \sum_{F \in F_h} \int_F \gamma^{k+1}_{\nabla,F} w_h f - \mu \left( \nabla^{k+1}_F I^{k}_{\nabla,F} u, \nabla^{k+1}_F w_h \right)_{\nabla,F} + \int_F D^k_F w_h \pi^k_{p,F} p - \int_F D^k_F I^k_{\nabla,F} w_h q_F
\]
\[= \sum_{F \in F_h} \int_F \gamma^{k+1}_{\nabla,F} w_h \cdot \text{grad } p + \int_F D^k_F w_h \pi^k_{p,F} p - \mu \left( \int_F \gamma^{k+1}_{\nabla,F} w_h \cdot \Delta u + \left( \nabla^{k+1}_F I^{k}_{\nabla,F} u, \nabla^{k+1}_F w_h \right)_{\nabla,F} \right)
\]
\[= \hat{E}_{\nabla,h}(p I_{L^2,F}(w_h)) - s_{L^2,F} \left( \nabla^{k+1}_F w_h, I^{k}_{L^2,F}(p I_{L^2,F}(w_h)) \right) \left( \Delta \hat{E}_{\nabla,h}(u,w_h) \leq |\hat{E}_{\nabla,h}(p I_{L^2,F}(w_h))| + |s_{L^2,F} \left( \nabla^{k+1}_F w_h, I^{k}_{L^2,F}(p I_{L^2,F}(w_h)) \right)|^{1/2}
\]
\[+ |s_{L^2,F} \left( I^{k}_{L^2,F}(p I_{L^2,F}(w_h)) \right)|^{1/2} + \mu |\hat{E}_{\nabla,h}(u,w_h)|.
\]
Here the second equality comes from we used $f = -\mu \Delta u + \text{grad} p$, (4.2b) and div $u = 0$, and the third equality comes from (5.11), (5.14) as well as:

$$\int_F D_F^k w_F \pi_F^k p_F = \int_F \text{Tr} \nabla^{k+1}_F w_F p = \int_F \nabla^{k+1}_F w_F : (p I_{2,2}) = \int_F \nabla^{k+1}_F w_F : \pi^{k+1}_E \mathbf{R}_F^k (p I_{2,2}) .$$

We conclude inferring the estimates Theorem 26, 28 and the consistency (5.4).

7 Alternative boundary conditions.

In this section we show how to extend the results of Section 6 when using Dirichlet boundary conditions on $X^k_{\nabla,h}$. This is useful for common condition such as the no slip condition or forced inlet condition and does not require much change.

7.1 Dirichlet boundary conditions.

We introduce the space $X^k_{\nabla,h,0} := \{ \psi_h \in X^k_{\nabla,h} : \forall E \in \mathcal{E}_h, E \subset \partial \Omega, \psi_E \equiv 0 \}$. The continuous and discrete problem are then pretty much the same: they take the same expression but on a different domain. Since the pressure is only defined up to a constant value, we introduce the natural space: $X^k_{L^2,h,*} := \{ q_h \in X^k_{L^2,h} : \sum_{F \in \mathcal{F}_h} \int_F q_F = 0 \}$. Then we define the bilinear form: $A_h((\psi_h, p_h), (\omega_h, q_h)) \in (X^k_{\nabla,h,0} \times X^k_{L^2,h,*}) \times (X^k_{\nabla,h,0} \times X^k_{L^2,h,*}) \to \mathbb{R}$ by

$$A_h((\psi_h, p_h), (\omega_h, q_h)) = a_h(\psi_h, \omega_h) - b_h(\psi_h, p_h) + b_h(\omega_h, q_h). \quad (7.1)$$

With $a_h$ and $b_h$ defined by (6.2), (6.3), we also keep the same definition (6.6) of the source term $L_h$. So the discrete problem is:

Find $(\psi_h, p_h) \in X^k_{\nabla,h,0} \times X^k_{L^2,h,*}$ such that for all $(\omega_h, q_h) \in X^k_{\nabla,h,0} \times X^k_{L^2,h,*}$

$$A_h((\psi_h, p_h), (\omega_h, q_h)) = L_h(\psi_h). \quad (7.2)$$

The Stokes problem becomes:

Find $u \in H^1_0(\Omega) \cap H^2(\Omega), p \in H^1(\Omega) \cap L^2(\Omega)$ such that

$$-\mu \Delta u + \text{grad} p = f, \text{ on } \Omega, \quad \text{div } u = 0, \text{ on } \Omega. \quad (7.3)$$

**Theorem 32.** Under the same assumption as Theorem 29 we obtain the well-posedness of the problem (7.2) and a convergence toward the continuous solution of problem (7.3) with the same error estimate as Theorem 29.

**Proof.** As stated before there is not much to adapt, namely: We need a suitable version of Lemma 24 and we can expect $\psi_h \in X^k_{\nabla,h,0}$ if $p_h \in X^k_{L^2,h,*}$. We also need to substitute the use of Theorem 43 by Theorem 44 and adapting the proof of Lemma 24. The consistency errors 26 and 28 required respectively $W \in H^1_0(\Omega)$ and $\nabla w \cdot n_\Omega = 0$. However we can check that this is only used to get (5.13) and (5.16), both of which also hold if $\psi_h \in X^k_{\nabla,h,0}$ instead, so that $v_E \equiv 0, \forall E \subset \partial \Omega$. Finally, we relied on Lemma 22 to show that $A_h$ is weakly coercive. This too can readily be adapted if we use [10, Lemma 2.15] instead of [10, Theorem 6.5] in the proof of Lemma 22. With these three results we can proceed exactly in the same manner as we did for Theorem 29. \(\square\)
7.2 Mixed boundary conditions.

We can also use Dirichlet conditions on a subset of the boundary and Neumann conditions elsewhere. Explicitly we write $\Gamma_D$ a relatively open subset of $\partial \Omega$ with a non-zero measure and $\Gamma_N = \partial \Omega \setminus \Gamma_D$. We also assume that each boundary edge $\partial \Omega \supset E \in \mathcal{E}_h$ is either contained in $\Gamma_N$ or in $\Gamma_D$ but not in both (either $E \cap \Gamma_D = \emptyset$ or $E \cap \Gamma_N = \emptyset$) and that both contained at least one edge (else we degenerate to pure Neumann or pure Dirichlet with have already been deals with). The boundary defined by $\Gamma_D$ will expectedly be where we use Dirichlet boundary conditions and $\Gamma_N$ where we use Neumann boundary conditions. So that the Stokes problem is:

Find $\mathbf{u} \in H^2(\Omega)$, $p \in H^1(\Omega)$ such that

$$
-\mu \Delta \mathbf{u} + \nabla p = f, \quad \text{on} \quad \Omega,
$$

$$
\text{div } \mathbf{u} = 0, \quad \text{on} \quad \Omega,
$$

$$
\mathbf{u} = 0, \quad \text{on} \quad \Gamma_D,
$$

$$
\frac{\partial \mathbf{u}}{\partial n} = 0, \quad \text{on} \quad \Gamma_N,
$$

$$
p = 0, \quad \text{on} \quad \Gamma_N. \tag{7.4}
$$

We introduce the discrete space $\mathbf{X}^k_{\nabla,h,D} := \{ \mathbf{v}_h \in \mathbf{X}^k_{\nabla,h} : \forall E \in \mathcal{E}_h, E \subset \Gamma_D, \mathbf{v}_E = 0 \}$ and as before define: $A_h((\mathbf{v}_h, p_h), (\mathbf{w}_h, q_h)) \in (\mathbf{X}^k_{\nabla,h,D} \times \mathbf{X}^k_{L^2,h}) \times (\mathbf{X}^k_{\nabla,h,D} \times \mathbf{X}^k_{L^2,h}) \to \mathbb{R}$ by

$$
A_h((\mathbf{v}_h, p_h), (\mathbf{w}_h, q_h)) = a_h(\mathbf{v}_h, \mathbf{w}_h) - b_h(\mathbf{w}_h, p_h) + b_h(\mathbf{v}_h, q_h). \tag{7.5}
$$

The discrete problem becomes once again:

Find $(\mathbf{v}_h, p_h) \in \mathbf{X}^k_{\nabla,h,D} \times \mathbf{X}^k_{L^2,h}$ such that for all $(\mathbf{w}_h, q_h) \in \mathbf{X}^k_{\nabla,h,D} \times \mathbf{X}^k_{L^2,h}$

$$
A_h((\mathbf{v}_h, p_h), (\mathbf{w}_h, q_h)) = \mathcal{L}_h(\mathbf{v}_h). \tag{7.6}
$$

Remark 33. In practical implementation we store continuous polynomials on edge by their lower order moment on each edge and their values on vertices. If a boundary edge is part of the Dirichlet boundary: $E \subset \Gamma_D$ we must set to zero all associated unknowns, including those on the vertices of this edge.

Remark 34. Although we took homogeneous boundary conditions for the sake of simplicity this is by no means a limitation. For inhomogeneous Dirichlet simply write $\mathbf{u} = \mathbf{u}_0 + \mathbf{u}_D$ with $\mathbf{u}_0 \in \mathbf{X}^k_{\nabla,h,D}$ and $\mathbf{u}_D$ given by the value on the boundary and solve for $\mathbf{u}_0$.

8 Numerical tests.

We display the numerical results for the Stokes problem with Neumann boundary conditions (7.7), with Dirichlet boundary conditions (7.2) and with mixed boundary conditions (7.6). This was implemented with the HArDCore C++ framework (see https://github.com/jdroniou/HArDCore), using the linear algebra facilities from the Eigen3 library (see https://eigen.tuxfamily.org). An implementation of the spaces and operators defined in this paper as well as a Stokes solver can be found at https://github.com/mlhanot/HArDCore2D-Stokes

We used a constant viscosity $\mu = 1$ and measure the rate of convergence for various polynomial degrees $k \in \{0, 1, 2, 3\}$. We compute the error by

$$
\| \mathbf{v}_h - I_{\nabla,h} \mathbf{u} \|_{\mu, \nabla, 1, h} + \| p_h - \pi^k_h p_h \|_{L^2,h}. \tag{7.8}
$$

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We expect the error to decrease at a rate $O(h^{k+1})$ thanks to Theorem 29 and 32. These tests are done on various mesh sequences which can be seen in Figure 2 showing the flexibility of the method. We show our results in Figure 3. We always obtain results consistent with the theory and the various features of the meshes do not deteriorate the convergence toward the exact solution.

A Results on polynomial spaces.

We begin by showing a few results to complete the introduction of spaces (2.12) and (2.14).

**Lemma 35.** For $x_F \in F$ the point given by (2.5) the set $\mathcal{R}^{c,k+1}(F)$ is explicitly given by:

$$\mathcal{R}^{c,k+1}(F) = \left\{ \frac{-((x-x_F)(y-y_F)Q}{(x-x_F)^2Q}, \frac{-(y-y_F)^2Q}{(x-x_F)(y-y_F)Q} \right\}, Q \in \mathcal{P}^{k-1}(F).$$

**Proof.** For all $R \in \mathcal{RT}^{c,k+1}$ there is $P_1, P_2 \in \mathcal{P}^k$ such that:

$$R = \begin{pmatrix} xP_1 \\ xP_2 \\ yP_1 \\ yP_2 \end{pmatrix}.$$

Since Tr $R = 0$ it holds $xP_1 = -yP_2$. Both $x$ and $y$ are prime in $\mathcal{P}[X,Y]$ so $\exists Q_1, Q_2 \in \mathcal{P}^{k-1}, P_1 = yQ_1, P_2 = xQ_2$. Hence $xyQ_1 = -yxQ_2, Q_1 = -Q_2$. \hfill \Box

**Lemma 36.** For any $F \in F_h$, it holds $\mathcal{R}^{c,k}(F) \cap \mathcal{R}^k(F) = \{0\}$. 

Figure 2: Families of mesh used.
Figure 3: Absolute error estimate in discrete norm $\| \cdot \|_{k, \nabla, 1, h} + \| \cdot \|_{L^2, h}$ vs. mesh size $h$. 
Proof. If \( w \in \mathcal{P}^{0,k}(F) \) and \( W \in (\mathcal{R}^{c,k}(F)^T)^2 \) are such that \( \text{Tr} W = 0 \) and \( \nabla \cdot W = \text{grad} w \) then \( W = 0 \) and \( w = 0 \). Indeed assuming \( x_F = 0 \) without loss of generality any element \( W \in \mathcal{R}^{c,k}(F) \) is written \( W = (xyP_{i,j}x^iy^j - x^2P_{i,j}x^iy^j - xyP_{i,j}x^iy^j) \), \( P_{i,j}x^iy^j \in \mathcal{P}^{k-2}(F) \). So that

\[
\nabla \cdot W = \left( (2+i+j)P_{i,j+1}x^iy^j \right).
\]

On the other side for \( w = w_{i,j}x^iy^j \in \mathcal{P}^{0,k}(F) \),

\[
\text{grad} w = \left( (i+1)w_{i+1,j}x^iy^j \right).
\]

Hence, \( \nabla \cdot W = \text{grad} w \) if and only if for all \( i, j \geq 0 \),

\[
\left( (1+i+j)P_{i-1,j-1} \right) = \left( i w_{i,j} \right).
\]

This is only satisfied for \( w = 0 \). \( \square \)

Lemma 37. For any \( F \in F_h \), it holds \( (\mathcal{R}^{c,k}(F)^T)^2 = \mathcal{R}^{c,k}(F) \oplus \mathcal{R}^k(F) \).

Proof. Lemma 36 already shows that \( \mathcal{R}^{c,k}(F) \cap \mathcal{R}^k(F) = \{0\} \). It is enough to compare the dimension of these spaces:

\[
\dim \mathcal{R}^{c,k}(F) = \dim \mathcal{P}^{k-2}(F) = \frac{k!}{2(k-2)!} = \frac{k(k-1)}{2},
\]

\[
\dim \mathcal{R}^k(F) = \dim \mathcal{P}^{0,k}(F) = \frac{(k+2)(k+1)}{2} - 1 = \frac{k^2 + 3k + 2 - 2}{2}.
\]

The sum of both is \( \frac{k^2 + 3k + k^2 - k}{2} = k(k+1) \), which is the same as

\[
\dim (\mathcal{R}^{c,k}(F)^T)^2 = 2 \dim \mathcal{P}^{k-1}(F) = 2 \frac{(k+1)k}{2} = k(k+1).
\]

Next we show some lemmas on convex polytopes.

Lemma 38. Let \( F \in F_h \), \( x_F \) defined as in (2.5), if \( B = B(x_F, h_B) \subset F \) with \( h_B \geq h_F \) and \( Q \in \mathcal{P}^k(F) \) then \( \|Q\|_{L^\infty(B)} \approx \|Q\|_\infty \).

Proof. Let \( h_o \in \mathbb{R}^*_+ \) such that \( F \subset B(x_F, h_o) \) and \( h_o \lesssim h_F \) \((h_o \) exists by the regularity assumption on the mesh sequence \( \mathcal{M}_h \)). Let \( v \) by any vector such that \( \|v\| = 1 \), then \( \forall \alpha > 0 \) such that \( x_F + \alpha v \in F \),

\[
Q(x_F + \alpha v) = \sum_{i=0}^{k} \frac{\partial_i^Q(x_F)}{i!} \alpha^i,
\]

so

\[
|Q(x_F + \alpha v)| \leq \sum_{i=0}^{k} \frac{\|\partial_i^Q\|_{L^\infty(B)}}{i!} \alpha^i.
\]

By the discrete Poincare inequality Lemma 2 we have \( \forall i, \|\partial_i^Q\|_{L^\infty(B)} \lesssim h_B^{-1} \|Q\|_{L^\infty(B)} \). Lastly \( x_F + \alpha v \in F \) so \( \alpha < h_o \) and \( |Q(x_F + \alpha v)| \approx \|Q\|_{L^\infty(B)} h_o^{-1} h_B^{-1} \). Since \( h_o \lesssim h_B \) we can conclude \( \|Q\|_\infty \lesssim \|Q\|_{L^\infty(B)} \). \( \square \)

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Any $F \in \mathcal{F}_h$ is a convex, open polygon. Let $(E_i)_{i \leq |\mathcal{E}_F|}$ be the set of its edges, each of normal vector $n_{E_i}$. For all $E_i$, there exists $P_i \in P^1(\mathbb{R}^2)$ such that $E_i \subset \text{Ker}(P_i)$, moreover we can normalize $P_i$ such that $\mathbf{x} \in F \implies P_i(\mathbf{x}) > 0$ (since $F$ is convex) and $|\partial n_{E_i} P_i| = 1$.

Lemma 39. Set $P = \prod_{i \leq |\mathcal{E}_F|} P_i$, $\mathbf{x}_0 \in F$ such that $B_0 = B(\mathbf{x}_0, h_F/2) \subset F$ and $B = B(\mathbf{x}_0, h_F/4)$ then $\inf_{\mathbf{x} \in B} P(\mathbf{x}) > \left(\frac{h_F}{4}\right)^{|\mathcal{E}_F|}$ and $\|P\|_{L^\infty(F)} \lesssim h_F^{|\mathcal{E}_F|}$.

Proof. For any $i \leq |\mathcal{E}_F|$, the value $P_i(\mathbf{x})$ at any point $\mathbf{x}$ is the distance between $\mathbf{x}$ and the straight line defined by $E_i$ and is positive on $F$. For any $\mathbf{x} \in B$, $\mathbf{x}$ is a least at a distance $h_F/4$ of any edge since $B_0 \subset F$. We obtain the lower bound by taking the product over all edges. Conversely, using the mesh regularity we can find $h_o > 0$, $h_o \lesssim h_F$ such that $F$ is inscribed in a circle of diameter $h_o$. Then $\forall i \leq |\mathcal{E}_F|$, $\forall \mathbf{x} \in F$, it holds $0 < P_i(\mathbf{x}) < h_o \lesssim h_F$. Again we conclude by taking the product over all edges.

Lemma 40. For any $F \in \mathcal{F}_h$ and $q \in \mathcal{P}^k(F)$ there is $P \in \mathcal{P}^{k+|\mathcal{E}_F|}(F)$ such that $P_{\partial F} = 0$, $\pi_{P,F} P = q$ and $\|P\| \approx \|q\|$. 

Proof. Let $P = \Pi Q$ with $\Pi$ given by Lemma 39 and $Q \in \mathcal{P}^k(F)$. The application

$$\mathcal{P}^{k}(F) \ni Q \mapsto \left( \lambda \mapsto \int_F Q \lambda \right) \in \mathcal{P}^{k}(F)'$$

is linear and between two spaces of same dimension, thus it is enough to check that it is injective. Let $Q \in \mathcal{P}^k(F)$ such that $\forall \lambda \in \mathcal{P}^k(F)$, $\int_F \Pi \lambda = 0$ hence $\int_F \Pi Q^2 = 0$. However since on $F$, $\Pi > 0$ we can define the function $\sqrt{\Pi} \in L^2(F)$ and have $\int_F \left(\sqrt{\Pi Q}\right)^2 = \|\sqrt{\Pi Q}\|^2 = 0$. So $\sqrt{\Pi Q} = 0$ and $Q \equiv 0$ which prove that (A.1) is injective thus prove the existence of a polynomial $P \in \mathcal{P}^{k+|\mathcal{E}_F|}(F)$ such that $P_{\partial F} = 0$ and $\pi_{P,F} P = q$. Let us show that $P$ also satisfy the norm equivalence: In particular we must have

$$\int_F (P - q) Q = 0$$
$$\int_F \Pi Q^2 = \int_F q Q$$

$$\|\sqrt{\Pi Q}\|_{L^\infty}^2 \leq \|\|Q\|_{L^\infty} \lesssim \|Q\| \|h_F\|_{L^\infty}.$$ 

Therefore the discrete Sobolev inequality [10, Lemma 1.25] gives

$$\|\sqrt{\Pi Q}\|_{L^\infty}^2 \approx h_F^{-2} \|\sqrt{\Pi Q}\|^2 \lesssim h_F^{-1} \|Q\|_{L^\infty} \|Q\|_{L^\infty}.$$

On the other consider $B = B(\mathbf{x}_0, h_F/4)$ given in Lemma 39, it holds $\inf_{\mathbf{x} \in B} \sqrt{\Pi}(\mathbf{x}) \gtrsim h_F^{|\mathcal{E}_F|}/2$. Thus by Lemma 39,

$$\|\sqrt{\Pi Q}\|_{L^\infty} \geq \|\sqrt{\Pi Q}\|_{L^\infty(B)} \gtrsim h_F^{|\mathcal{E}_F|}/2 \|Q\|_{L^\infty(B)} \approx h_F^{|\mathcal{E}_F|}/2 \|Q\|_{L^\infty}.$$ 

Hence $h_F^{|\mathcal{E}_F|} \|Q\|_{L^\infty}^2 \lesssim h_F^{-1} \|Q\|_{L^\infty} \|Q\|_{L^\infty}$, $\|Q\|_{L^\infty} \lesssim h_F^{-1-|\mathcal{E}_F|} \|Q\|_1$ and

$$\|\Pi Q\| \approx h_F \|\Pi Q\|_{L^\infty} \leq h_F \|\Pi\|_{L^\infty} \|Q\|_{L^\infty} \lesssim h_F^{|\mathcal{E}_F|+1} \|Q\|_{L^\infty} \lesssim \|Q\|.$$ 

29
B Trace lifting.

In order to prove consistency results we often need functions of Sobolev spaces with suitable properties. We construct them in this section.

**Theorem 41.** For all \( \nu_F \in X_{\nu,F}^k \) there is \( R_{\nu_F} \in H^1(F) \) such that
\[
R_{\nu_F} = \nu_F \text{ on } \partial F, \\
\|R_{\nu_F}\|_F + \|\nabla R_{\nu_F}\|_F \lesssim \|\nu_F\|_{\nabla,F} + \left\|\nabla^{k+1} \nu_F\right\|_{L^2,F}.
\]
(B.1)

This lift is built upon [2, Theorem 18.40]: Let \( \Omega \subset \mathbb{R}^N, N \geq 2 \) be an open set whose boundary \( \partial \Omega \) is uniformly Lipschitz continuous of parameters \( \epsilon, L \) and \( M \) (see [2, Definition 13.11]). Then for all \( g \in B^{1/2,2}(\partial \Omega) \), there is \( c \in \mathbb{R} \) depending only on \( N \) and a function \( u \in H^1(\Omega) \) such that \( \text{Tr}(u) = g \),
\[
\|u\|_{L^2(\Omega)} \leq M^{1/2} \epsilon^{1/2} \|g\|_{L^2(\partial \Omega)} \tag{B.2}
\]
and
\[
\|\text{grad} u\|_{L^2(\Omega)} \leq cM(1 + L)^{3N/2} \epsilon^{-1/2} \|g\|_{L^2(\partial \Omega)} + cM(1 + L)^{2N} \|g\|_{B^{1/2,2}(\partial \Omega)}^{\circ} \tag{B.3}
\]
With the Besov seminorm defined by (see [2, Definition 18.36]):
\[
|g|_{B^{1/2,2}(\partial \Omega)}^{\circ} := \left( \int_{\partial \Omega} \int_{\partial \Omega \cap B(x,\epsilon)} \frac{(g(x) - g(y))^2}{|x - y|^N} dy dx \right)^{1/2}. \tag{B.4}
\]

**Proof of theorem 41.** We apply the above-mentioned theorem [2, Theorem 18.40] to \( \Omega = F \) and \( g \) a component of \( \nu_{\nu,F} \). Here \( N = 2 \) and for the open cover of \( \partial F \) (see [2, Definition 13.11]) we take a ball centered at each vertex of radius half the length of the shortest adjacent edge as well as a ball centered on middle of each edge of radius half the length of the edge. This way we have \( L = 1 \), \( M = 2 \) and \( \epsilon \approx h_F \). We conclude with the estimate on the Besov seminorm Lemma 42.

Indeed, let \( R_{\nu_F} \) be such that \( \text{Tr}(R_{\nu_F}) = \nu_{\nu,F} \) and that \( R_{\nu_F} \) satisfy (B.2) and (B.3). Let \( g \) be a component of \( \nu_{\nu,F} \) and \( u \) be given by (B.2) and (B.3). Without loss of generality we assume that \( \int_{\partial F} g = 0 \): Else we take instead \( \bar{g} = \int_{\partial F} g \) and \( u = \bar{g} \), \( \text{grad } u = 0 \) and \( \|u\|_{L^2(\Omega)} \approx h_F^2 |\bar{g}| \), \( |\bar{g}|_{L^2(\partial F)} \approx h_F |\bar{g}| \) and \( u, \bar{g} \) satisfy (B.1). We reduce to the case \( \int_{\partial F} g' = 0 \) for \( g' = g - \bar{g} \).

Equation (B.2) gives \( \|R_{\nu_F}\|_F \lesssim \|\nu_F\|_{\nabla,F} \) since \( \epsilon \approx h_F \). Applying the Poincare-Wirtinger inequality to \( \partial F \) (since \( g \) is continuous and assumed to have zero average) we get \( \|g\|_{L^2(\partial F)} \lesssim h_F \|g'\|_{L^2(\partial F)} \), hence
\[
\|\text{grad } u\|_{L^2(\Omega)} \lesssim h_F^{-1} \|g\|_{L^2(\partial F)} + |g|_{B^{1/2,2}(\partial \Omega)}^{\circ} \\
\lesssim h_F^{-1} h_F \|g'\|_{L^2(\partial F)} + h_F^{-1} \|g'\|_{L^2(\partial F)}^{\circ} \\
\lesssim h_F^{-1} \|g'\|_{L^2(\partial F)}^{\circ}.
\]
Recalling definitions (3.28) and (3.14) we get the expected results. \( \square \)

**Lemma 42.** Keeping the notations of the proof of Theorem 41 it holds
\[
|g|_{B^{1/2,2}(\partial \Omega)}^{\circ} \lesssim h_F^{1/2} \|g'\|_{L^2(\partial \Omega)}. \tag{B.5}
\]
Proof. We know that $g$ is a continuous piecewise polynomial. Let $E \in \mathcal{E}_F$. Far away from the vertices, i.e. for $x \in E$ such that $B(x, \epsilon) \cap V_F = \emptyset$ it holds $\forall y \in B(x, \epsilon)$, $\exists \epsilon \in B(x, \epsilon)$ such that

$$g(x) = g(y) + g'(y)(x - y) + g''(c)\frac{(x - y)^2}{2}.$$ 

Hence

$$\frac{|g(x) - g(y)|^2}{\|x - y\|^2} = \frac{|g'(y)(x - y) + g''(c)(x - y)^2|}{\|x - y\|^2} \leq |g'(y)(x - y)| + \frac{|g''(c)(x - y)^2|}{\|x - y\|^2} \leq \|g'(y)\|^2 + \|g''(c)\|^2\|x - y\|^2.$$ 

If $x_V$ is the curvilinear coordinate of a vertex of $E$, the formula still holds for $g(x) - g(x_V)$ since $g$ is continuous on $[x, x_V]$ and $C^\infty$ on $[x, x_V]$. Thus the formula holds for all $x$, $y$ using the triangular inequality if $x$ and $y$ are not on the same edge. Moreover, since $\epsilon \approx h_F$ and $\int_{\partial F} 1 \approx h_F$ it holds:

$$\int_{x \in \partial F} \int_{y \in \partial F \cap B(x, \epsilon)} \|g''\|^2_\infty|\|x - y\|^2 \leq \int_{x \in \partial F} \frac{4}{3} \epsilon^3 \int_{x \in \partial F} \|g''\|^2 \lesssim \|g''\|^2_\infty h_F^4.$$ 

We have $\|g''\|_\infty \lesssim h_F^{-1} \|g''\|_{L^2(\partial F)}$ by Lemma 1.25, $\|g''\|_{L^2(\partial F)} \lesssim h_F^{-1} \|g''\|_{L^2(\partial F)}$ by Lemma 2 so $\|g''\|^2 \lesssim h_F^{-3} \|g''\|^2_{L^2(\partial F)}$ and

$$\int_{x \in \partial F} \int_{y \in \partial F \cap B(x, \epsilon)} \|g''(x - y)\|^2 \lesssim h_F \|g''\|_{L^2(\partial F)}.$$ 

On the other hand by Fubini-Tonelli it holds

$$\int_{x \in \partial F} \int_{y \in \partial F \cap B(x, \epsilon)} |g'(y)|^2 = \int_{x \in \partial F} \int_{y \in \partial F} |g'(y)|^2 1_{B(x, \epsilon)}(y) = \int_{y \in \partial F} |g'(y)|^2 \int_{x \in \partial F} 1_{B(x, \epsilon)}(y).$$ 

However $\int_{x \in \partial F} 1_{B(x, \epsilon)}(y) \lesssim h_F$ thus

$$\int_{x \in \partial F} \int_{y \in \partial F \cap B(x, \epsilon)} |g'(y)|^2 \lesssim h_F \|g'\|^2_{L^2(\partial F)}.$$ 

\[\square\]

**Theorem 43.** If $p \in H^1_0(\Omega)$ then there is $u \in H^2(\Omega)$ such that $\text{div} u = p$, $\|u\|_{H^2} \lesssim \|p\|_{H^1}$ and $\|u\|_{H^1} \lesssim \|p\|_{L^2}$.

**Proof.** Consider a smooth bounded extension (at least $C^{2,1}$) $B$ of $\Omega$. For all function $g \in H^{-1}(B)$, following [4] Theorem III.4.1 there is a unique solution $f \in H^1_0(B)$ to the equation $\Delta f = g$ in $B$. Moreover this solution satisfy $\|f\|_{H^1} \lesssim \|g\|_{H^{-1}}$ and [4] Theorem III.4.2 shows that if $B$ is $C^{k+1,1}$, $k \geq 0$ and $g \in H^k(B)$ then $\|f\|_{H^{k+2}} \lesssim \|g\|_{H^k}$. Since $p \in H^1_0(\Omega)$ we can extend $p$ by zero and define $\tilde{p} \in H^1_0(B)$ with $\|\tilde{p}\|_{H^1} = \|p\|_{H^1_0(\Omega)}$. Hence if we take $f \in H^1_0(B)$ such that $\Delta f = \text{div} \, g \tilde{f} = \tilde{p}$ we have $f \in H^3(B)$ since $\tilde{p} \in H^1(B)$ with $\|f\|_{H^3(B)} \lesssim \|p\|_{L^2}$ and $\|f\|_{H^2(B)} \lesssim \|p\|_{H^1}$. Let $u = \text{grad} \, f_{|\Omega}$ then we have $\text{div} \, u = \tilde{p}$ in $\Omega$ and the expected bounds.  

\[\square\]
We can adapt the theorem to cover other boundary conditions.

**Theorem 44.** If $B \subset \Omega$ is $C^{2,1}$, $p \in H^1(B)$ such that $\int_B p = 0$ then there is $u \in H^1_0(B) \cap H^2(B)$ such that $\text{div}\ u = p$, $\|u\|_{H^1} \lesssim \|p\|_{H^{1/2}}$ and $\|u\|_{H^2} \lesssim \|p\|_{L^2}$.

**Proof.** The proof is similar to the one of Theorem 43 using [4, Theorem III.4.3] instead of [4], Theorem III.4.1].

### References

[1] Susanne C. Brenner and L. Ridgway Scott. *The Mathematical Theory of Finite Element Methods*. 3rd ed. Texts in Applied Mathematics. Springer New York, 2008. doi: [10.1007/978-0-387-75934-0](https://doi.org/10.1007/978-0-387-75934-0).

[2] Giovanni Leoni. *A first course in Sobolev spaces*. Graduate Studies in Mathematics. American Mathematical Society, 2009.

[3] D. N. Arnold, R. S. Falk, and J. Gopalakrishnan. “Mixed finite element approximation of the vector Laplacian with Dirichlet boundary conditions”. In: *Math. Models Methods Appl. Sci.* 22.09 (2012), p. 1250024. doi: [10.1142/s0218202512500248](https://doi.org/10.1142/s0218202512500248).

[4] Pierre Fabrie (auth.) Franck Boyer. *Mathematical Tools for the Study of the Incompressible Navier-Stokes Equations and Related Models*. 1st ed. Applied Mathematical Sciences 183. Springer-Verlag New York, 2013.

[5] Michael Neilan. “Discrete and conforming smooth de Rham complexes in three dimensions”. In: *Math. Comp.* 84 (2015), 2059-2081 (2015). doi: [10.1090/s0025-5718-2015-02958-5](https://doi.org/10.1090/s0025-5718-2015-02958-5).

[6] Volker John et al. “On the Divergence Constraint in Mixed Finite Element Methods for Incompressible Flows”. In: 59.3 (Jan. 2017), pp. 492–544. doi: [10.1007/s10092-017-0282-3](https://doi.org/10.1007/s10092-017-0282-3).

[7] Douglas N. Arnold. *Finite Element Exterior Calculus*. Vol. 93. CBMS-NSF Regional Conference Series in Applied Mathematics. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 2018, pp. xii+120.

[8] Daniele A. Di Pietro and Jérôme Droniou. “A third Strang lemma and an Aubin–Nitsche trick for schemes in fully discrete formulation”. In: *Calcolo* 55.3 (Sept. 2018). doi: [10.1007/s10092-018-0282-3](https://doi.org/10.1007/s10092-018-0282-3).

[9] Daniele A. Di Pietro, Jérôme Droniou, and Francesca Rapetti. “Fully discrete polynomial de Rham sequences of arbitrary degree on polygons and polyhedra”. In: *Mathematical Models and Methods in Applied Sciences* 30.09 (Aug. 2020), pp. 1809–1855. doi: [10.1142/s0218202520500372](https://doi.org/10.1142/s0218202520500372).

[10] Daniele Antonio Di Pietro and Jérôme Droniou. *The Hybrid High-Order Method for Polytopal Meshes*. Modeling, Simulation and Applications series. Springer International Publishing, Mar. 2020. doi: [10.1007/978-3-030-37203-3](https://doi.org/10.1007/978-3-030-37203-3).

[11] Kaibo Hu, Qian Zhang, and Zhimin Zhang. “A family of finite element Stokes complexes in three dimensions”. In: (2020). arXiv: [2008.03793 [math.NA]](https://arxiv.org/abs/2008.03793).

[12] Xuehai Huang. *Nonconforming finite element Stokes complexes in three dimensions*. 2020. arXiv: [2007.14068 [math.NA]](https://arxiv.org/abs/2007.14068).

[13] L. Beirão da Veiga, F. Dassi, and G. Vacca. “The Stokes complex for Virtual Elements in three dimensions”. In: 30.03 (Mar. 2020), pp. 477–512. doi: [10.1142/s0218202520500128](https://doi.org/10.1142/s0218202520500128).
[14] Daniele Antonio Di Pietro and Jérôme Droniou. “An arbitrary-order discrete de Rham complex on polyhedral meshes: Exactness, Poincaré inequalities, and consistency”. In: (2021). arXiv:2101.04940 [math.NA].