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► **To cite this version:**

Daniele Antonio Di Pietro, Jérôme Droniou. Homological- and analytical-preserving serendipity framework for polytopal complexes, with application to the DDR method. *ESAIM: Mathematical Modelling and Numerical Analysis*, 2023, 57 (1), pp.191-225. 10.1051/m2an/2022067 . hal-03598859

HAL Id: hal-03598859

<https://hal.science/hal-03598859v1>

Submitted on 6 Mar 2022

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Homological- and analytical-preserving serendipity framework for polytopal complexes, with application to the DDR method

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March 6, 2022

Abstract

In this work we investigate from a broad perspective the reduction of degrees of freedom through serendipity techniques for polytopal methods compatible with Hilbert complexes. We first establish an abstract framework that, given two complexes connected by graded maps, identifies a set of properties enabling the transfer of the homological and analytical properties from one complex to the other. This abstract framework is designed having in mind discrete complexes, with one of them being a reduced version of the other, such as occurring when applying serendipity techniques numerical methods. We then use this framework as an overarching blueprint to design a serendipity DDR complex. Thanks to the combined use of higher-order reconstructions and serendipity, this complex compares favorably in terms of DOF count to all the other polytopal methods previously introduced and also to finite elements on certain element geometries. The gain resulting from such a reduction in the number of DOFs is numerically evaluated on a model problem inspired by magnetostatics.

Key words. discrete de Rham method, Virtual Element method, compatible discretisations, polyhedral methods, serendipity

MSC2010. 65N30, 65N99, 65N12, 78A30

1 Introduction

The development of approximation methods for partial differential equations supporting general polytopal meshes and arbitrary order has been an extremely active field of research since the early 2010s; a representative but by far non exhaustive list of references includes [1, 3, 8, 12, 16, 18–20]. Recent efforts have focused on the compatibility of polytopal methods with Hilbert complexes; see, in particular, [4, 7] and [14, 17] concerning, respectively, Virtual Element (VEM) and Discrete de Rham (DDR) methods, as well as [10], where bridges between these technologies have been built. Compatible polytopal methods are based on discrete versions of the relevant Hilbert complex involving finite-dimensional (discrete) spaces connected by differential operators or discrete counterparts thereof. This sequence of discrete spaces and operators is built so as to preserve the homological properties of the original Hilbert complex.

Vanilla versions of polytopal methods often display more degrees of freedom (DOFs) than the corresponding finite element counterparts. A remedy to this drawback has been proposed in [6], where a version of the nodal (H^1 -conforming) VEM space with fewer face DOFs has been introduced. The idea, inspired by serendipity finite elements, consists in selecting a subset of the DOFs sufficient to identify uniquely polynomials of the desired degree, and in using them to fix the values of the remaining DOFs. A similar path had been previously followed in [13] to reduce the number of element DOFs in

the framework of discontinuous Galerkin methods. In the context of low-order methods, this approach is also called barycentric elimination [22], and has been used to eliminate cell unknowns in hybrid methods [23].

Serendipity techniques for DOFs reduction are appealing for several reasons: they make it possible to interface finite element and polytopal methods on standard geometries, as argued in [6]; they lead to smaller algebraic systems by reducing the number of face DOFs (which cannot be, in general, eliminated by static condensation); in the context of nonlinear problems, they provide a means to eliminate (a portion of the) element DOFs that is potentially more efficient than static condensation, as the serendipity reduction operators need not be recomputed at each iteration of the nonlinear solver, unlike the static condensation operators.

In the context of compatible polytopal methods, serendipity techniques have to be applied in a compatible manner in order to preserve the homological and analytical properties of the discrete complex. Concerning VEM methods, the issue of face DOFs reduction through compatible serendipity techniques has been considered in [5, 9], where the authors build a virtual serendipity de Rham complex for which they provide a direct proof of local exactness properties; see, in particular, [5, Propositions 3.2, 3.6, and 3.8]. A variation of the VEM complex in the previous reference has been recently proposed in [10], where links with DDR have also been established.

Inspired by these recent results, we tackle in this paper the issue of compatible serendipity polytopal complexes from a broader perspective. Specifically, we start by constructing an abstract framework that, given two complexes connected by graded maps, identifies a set of requirements on the serendipity operators that enable the transfer of all the relevant homological and analytical results from one complex to the other. In particular, the properties we identify ensure that the original and serendipity complexes have the same cohomologies, even in the case of non-exact complexes due to non-trivial topologies of the domain. Moreover, the identification of sufficient conditions for the preservation of analysis results such as Poincaré inequalities, primal and adjoint consistency, etc. in a general nonconforming setting seems to be an entirely new result (in a conforming setting, the preservation of such properties is significantly easier). This general framework is specifically adapted to the situation where one complex is a reduced version of the other, and the graded connecting maps are extensions/reductions which transfer properties from the full complex to the reduced one. This framework then enables us to derive a serendipity version (hereafter referred to as “SDDR”) of the DDR complex of [14]. The SDDR complex hinges on novel serendipity operators that rely on the same construction for both the discrete H^1 and $\mathbf{H}(\mathbf{curl})$ spaces, and that enable the reduction of both faces and element DOFs. The fulfillment of the requirements identified in the abstract framework ensures that the full panel of homological and analytical results derived in [14] transfers to the serendipity DDR complex. The new DDR complex is extremely efficient as it combines the use of higher-order reconstructions, typical of DDR, with serendipity on both faces and elements. The DOFs count therefore compares favorably to existing polytopal de Rham complexes [5, 7, 10, 15, 17], but also to finite elements on hexahedra (while being very close, although slightly higher, on tetrahedra); see Table 2 below. Serendipity versions of finite elements on cubical meshes have been recently explored with a DOF count comparable to the present construction (see, e.g., [24] and references therein), but an analysis and shape functions only presented for the lowest-order degree. The method discussed here is more general as it applies to general polyhedral elements, and is additionally designed so as to preserve the commutation properties between the interpolator and discrete differential operators discussed in [14, Section 3.5]. Having clarified the requirements for compatible serendipity techniques through an abstract framework also enables us to provide an answer to an open question left in [9], namely whether it is possible to perform DOF reduction on the $\mathbf{H}(\mathbf{div})$ discrete spaces in a compatible manner. Specifically, we prove in this paper that such a reduction is not possible as it would violate crucial requirements of the discrete complex.

The rest of the paper is organised as follows. In Section 2 we develop an abstract framework for the

preservation of the homological and analytical properties in reduced complexes. Section 3 contains a description of the setting (mesh, polynomial spaces), while the original DDR complex of [14] is briefly recalled in Section 4. The construction of the novel serendipity DDR complex is detailed in Section 5 and its properties are proved in Section 6, which also contains numerical tests to assess the performance gain resulting from the reduction of DOFs. Finally, Appendix A contains the proofs of estimates of polynomials from boundary values that are at the origin of the design of the serendipity operators.

2 Blueprint for homological and analytical properties preservation in reduced complexes

Consider a sequence $(X_i, d_i)_i$ of spaces and operators defining a complex, each space being associated to a (possibly vector-valued) polynomial space \mathcal{P}^{k_i} dictating the degree of polynomial consistency expected from the space and the discrete operator, and an interpolator $I_i : \mathcal{P}^{k_i} \rightarrow X_i$.

$$\begin{array}{ccccccc}
 & & \mathcal{P}^{k_i} & & \mathcal{P}^{k_{i+1}} & & \\
 & & \downarrow I_i & & \downarrow I_{i+1} & & \\
 \cdots & \longrightarrow & X_i & \xrightarrow{d_i} & X_{i+1} & \longrightarrow & \cdots \\
 & & \uparrow E_i & \text{---} & \uparrow E_{i+1} & & \\
 & & \hat{X}_i & \xrightarrow{\hat{d}_i} & \hat{X}_{i+1} & \longrightarrow & \cdots
 \end{array}
 \tag{2.1}$$

Assume that we have a second sequence of spaces $(\hat{X}_i)_i$, and connecting linear graded maps E and \hat{R} (the former being called *extensions*, the latter *reductions*) as in Diagram (2.1), and set, for all index i ,

$$\hat{d}_i := \hat{R}_{i+1} d_i E_i. \tag{2.2}$$

Having this diagram in mind, we will refer to $(X_i, d_i)_i$ as the *top sequence* and to $(\hat{X}_i, \hat{d}_i)_i$ as the *bottom sequence*. We now list properties that ensure that the two sequences have the same cohomology.

Assumption 1 (Homological properties). **(C1)** \hat{R}_i is a left-inverse of E_i on $\ker \hat{d}_{i+1}$, that is: $(\hat{R}_i E_i)|_{\ker \hat{d}_{i+1}} = \text{Id}_{\ker \hat{d}_{i+1}}$.

(C2) $(E_{i+1} \hat{R}_{i+1} - \text{Id}_{X_{i+1}})(\ker d_{i+1}) \subset \text{Im } d_i$,

(C3) Both the reduction and extension are cochain maps, i.e., $\hat{R}_{i+1} d_i = \hat{d}_i \hat{R}_i$ and $E_{i+1} \hat{d}_i = d_i E_i$. Equivalently, recalling the definition (2.2) of \hat{d}_i , $\hat{R}_{i+1} d_i = \hat{R}_{i+1} d_i E_i \hat{R}_i$ and $E_{i+1} \hat{R}_{i+1} d_i E_i = d_i E_i$.

Proposition 2 (Isomorphic cohomologies). *Under Assumption 1, the sequence $(\hat{X}_i, \hat{d}_i)_i$ is a complex and the cohomologies of $(X_i, d_i)_i$ and $(\hat{X}_i, \hat{d}_i)_i$ are isomorphic. In particular, if one complex is exact then so is the other.*

Proof. The fact that $(\hat{X}_i, \hat{d}_i)_i$ is a complex follows from **(C2)**. Denoting now the cohomology groups by $\mathcal{H}_i := \ker d_i / \text{Im } d_{i-1}$ and $\hat{\mathcal{H}}_i := \ker \hat{d}_i / \text{Im } \hat{d}_{i-1}$, by **(C3)** we can project E_i and \hat{R}_i on these groups, defining $[E_i] : \hat{\mathcal{H}}_i \rightarrow \mathcal{H}_i$ and $[\hat{R}_i] : \mathcal{H}_i \rightarrow \hat{\mathcal{H}}_i$. By **(C1)**, we have $[\hat{R}_i][E_i] = \text{Id}_{\hat{\mathcal{H}}_i}$ and, by **(C2)** for $i-1$, $[E_i \hat{R}_i - \text{Id}_{X_i}] = 0$, so that $[E_i][\hat{R}_i] = \text{Id}_{\mathcal{H}_i}$. This proves that $[E_i] : \hat{\mathcal{H}}_i \rightarrow \mathcal{H}_i$ and $[\hat{R}_i] : \mathcal{H}_i \rightarrow \hat{\mathcal{H}}_i$ are isomorphisms. \square

Our goal now is to deduce analytical properties of the bottom sequence based on corresponding properties of the top sequence. To do so, we assume that each X_i is equipped with an inner product

$(\cdot, \cdot)_{X,i}$, with norm $\|\cdot\|_{X,i}$. The inner product $(\cdot, \cdot)_{\hat{X},i}$ and associated norm $\|\cdot\|_{\hat{X},i}$ on \hat{X}_i are defined so that E_i is an isometry, that is:

$$(\hat{x}, \hat{y})_{\hat{X},i} := (E_i \hat{x}, E_i \hat{y})_{X,i} \quad \text{and} \quad \|\hat{x}\|_{\hat{X},i} = \|E_i \hat{x}\|_{X,i} \quad \forall (\hat{x}, \hat{y}) \in \hat{X}_i \times \hat{X}_i. \quad (2.3)$$

Of importance when considering discrete complexes is the degree of polynomial consistency they preserve, which is measured through the interpolators I_i in (2.1). Oftentimes, some properties involving interpolators on larger spaces are also useful. We will therefore consider that, for each X_i , there is a Hilbert space $\mathcal{H}_i \supset \mathcal{P}^{k_i}$ such that the interpolator I_i can be extended as $I_i : \mathcal{H}_i \rightarrow X_i$. The norm on \mathcal{H}_i is denoted by $\|\cdot\|_{\mathcal{H},i}$, and we define interpolator for the bottom sequence by:

$$\hat{I}_i := \hat{R}_i I_i : \mathcal{H}_i \rightarrow \hat{X}_i. \quad (2.4)$$

To properly define the interpolator, the norm on \mathcal{H}_i is typically quite “strong” (this space corresponds to a Sobolev space). Some estimates and consistency properties will require an “ L^2 -like” space \mathcal{L}_i (with inner product $(\cdot, \cdot)_{\mathcal{L},i}$ and norm $\|\cdot\|_{\mathcal{L},i}$) in which \mathcal{H}_i is continuously embedded. We denote by $c_{\mathcal{H},i}$ the embedding constant such that

$$\|v\|_{\mathcal{L},i} \leq c_{\mathcal{H},i} \|v\|_{\mathcal{H},i} \quad \forall v \in \mathcal{H}_i. \quad (2.5)$$

We now cite three assumptions that are involved in deducing analytical properties of the bottom sequence from properties of the top sequence.

Assumption 3 (Analytical properties).

(A1) *Continuity of reductions:* $\hat{R}_i : X_i \rightarrow \hat{X}_i$ is continuous, with norm denoted by $\|\hat{R}_i\|$.

(A2) *Polynomial consistency:* \hat{R}_i is a right-inverse of E_i on the subspace $I_i(\mathcal{P}^{k_i})$; recalling (2.4), this translate into: $E_i \hat{I}_i x_p = I_i x_p$ for all $x_p \in \mathcal{P}^{k_i}$.

(A3) *Continuity of interpolator:* $I_i : \mathcal{H}_i \rightarrow X_i$ is continuous for the norms $\|\cdot\|_{\mathcal{H},i}$ and $\|\cdot\|_{X,i}$, with norm denoted by $\|I_i\|$.

Proposition 4 (Poincaré inequality). *Assume (C3) and (A1). If (X_i, d_i) satisfies a Poincaré inequality, then so does (\hat{X}_i, \hat{d}_i) . More specifically, if there is $c_P \geq 0$ such that*

$$\|x\|_{X,i} \leq c_P \|d_i x\|_{X,i+1} \quad \forall x \in (\ker d_i)^\perp, \quad (2.6)$$

then

$$\|\hat{x}\|_{\hat{X},i} \leq c_P \|\hat{R}_i\| \|\hat{d}_i \hat{x}\|_{\hat{X},i+1} \quad \forall \hat{x} \in (\ker \hat{d}_i)^\perp.$$

Proof. The proof is inspired by that done for conforming discrete complexes in [2, Theorem 5.3]. Let $\hat{x} \in (\ker \hat{d}_i)^\perp$. Since $d_i : (\ker d_i)^\perp \rightarrow \text{Im } d_i$ is an isomorphism, there is $x \in (\ker d_i)^\perp$ such that $d_i x = d_i E_i \hat{x}$. Using the cochain map property (C3) for the reduction, we infer that $\hat{d}_i \hat{R}_i x = \hat{R}_{i+1} d_i x = \hat{R}_{i+1} d_i E_i \hat{x} = \hat{d}_i \hat{x}$, and thus that $\hat{R}_i x - \hat{x} \in \ker \hat{d}_i$. Hence, $\hat{x} \perp (\hat{x} - \hat{R}_i x)$, which gives

$$\|\hat{x}\|_{\hat{X},i}^2 = (\hat{x}, \hat{x})_{\hat{X},i} = (\hat{x}, \hat{R}_i x)_{\hat{X},i} \leq \|\hat{x}\|_{\hat{X},i} \|\hat{R}_i x\|_{\hat{X},i} \leq \|\hat{x}\|_{\hat{X},i} \|\hat{R}_i\| \|x\|_{X,i},$$

where the last inequality follows from (A1). Simplifying by $\|\hat{x}\|_{\hat{X},i}$ and applying (2.6), we obtain

$$\|\hat{x}\|_{\hat{X},i} \leq c_P \|\hat{R}_i\| \|d_i x\|_{X,i+1} = c_P \|\hat{R}_i\| \|d_i E_i \hat{x}\|_{X,i+1} = c_P \|\hat{R}_i\| \|E_{i+1} \hat{d}_i \hat{x}\|_{X,i+1},$$

where we have used the cochain map property of the extensions in the last equality. The proof is completed by recalling that E_{i+1} is an isometry. \square

Proposition 5 (Primal consistency of inner products). *Assume (A2), (A3), and suppose that the top sequence satisfies the polynomial consistency property*

$$(I_i v_p, I_i w_p)_{X,i} = (v_p, w_p)_{\mathcal{L},i} \quad \forall v_p, w_p \in \mathcal{P}^{k_i}.$$

Then, the bottom sequence satisfies the following properties:

1. Polynomial consistency:

$$(\hat{I}_i v_p, \hat{I}_i w_p)_{\hat{X},i} = (v_p, w_p)_{\mathcal{L},i} \quad \forall v_p, w_p \in \mathcal{P}^{k_i}. \quad (2.7)$$

2. Consistency in \mathcal{H}_i : Assuming (A1), for all $v, w \in \mathcal{H}_i$,

$$\begin{aligned} |(\hat{I}_i v, \hat{I}_i w)_{\hat{X},i} - (v, w)_{\mathcal{L},i}| &\leq \left(\|\hat{R}_i\|^2 \|I_i\|^2 + c_{\mathcal{H},i}^2 \right) \\ &\quad \times (\omega_{\mathcal{H},\mathcal{P},i}(v) \|w\|_{\mathcal{H},i} + \omega_{\mathcal{H},\mathcal{P},i}(w) \|v\|_{\mathcal{H},i} + \omega_{\mathcal{H},\mathcal{P},i}(v) \omega_{\mathcal{H},\mathcal{P},i}(w)), \end{aligned}$$

where $\omega_{\mathcal{H},\mathcal{P},i}$ measures the best polynomial approximation error in the norm of \mathcal{H}_i , i.e.,

$$\omega_{\mathcal{H},\mathcal{P},i}(\xi) := \inf_{\xi_p \in \mathcal{P}^{k_i}} \|\xi - \xi_p\|_{\mathcal{H},i} \quad \forall \xi \in \mathcal{H}_i.$$

Proof. For the polynomial consistency we simply write, for $v_p, w_p \in \mathcal{P}^{k_i}$,

$$(\hat{I}_i v_p, \hat{I}_i w_p)_{\hat{X},i} \stackrel{(2.3)}{=} (E_i \hat{I}_i v_p, E_i \hat{I}_i w_p)_{X,i} \stackrel{(A2)}{=} (I_i v_p, I_i w_p)_{X,i} = (v_p, w_p)_{\mathcal{L},i}.$$

We now turn to the consistency on \mathcal{H}_i . Let $v, w \in \mathcal{H}_i$, and take arbitrary $v_p, w_p \in \mathcal{P}^{k_i}$. Introducing $\pm \hat{I}_i v_p$ and $\pm \hat{I}_i w_p$ we have

$$(\hat{I}_i v, \hat{I}_i w)_{\hat{X},i} = (\hat{I}_i(v - v_p), \hat{I}_i w)_{\hat{X},i} + (\hat{I}_i v_p, \hat{I}_i(w - w_p))_{\hat{X},i} + (\hat{I}_i v_p, \hat{I}_i w_p)_{\hat{X},i}. \quad (2.8)$$

Invoking the polynomial consistency (2.7), we can write, for the last term in (2.8),

$$(\hat{I}_i v_p, \hat{I}_i w_p)_{\hat{X},i} = (v_p, w_p)_{\mathcal{L},i} = (v_p - v, w_p)_{\mathcal{L},i} + (v, w_p - w)_{\mathcal{L},i} + (v, w)_{\mathcal{L},i}.$$

Plugging this into (2.8) and using $\|\hat{I}_i v\|_{\hat{X},i} \leq \|\hat{R}_i\| \|I_i\| \|v\|_{\mathcal{H},i}$ for all $v \in \mathcal{H}_i$ (which results from (A1) and the continuity assumption on I_i) along with (2.5), we obtain

$$\begin{aligned} |(\hat{I}_i v, \hat{I}_i w)_{\hat{X},i} - (v, w)_{\mathcal{L},i}| &\leq \|\hat{R}_i\|^2 \|I_i\|^2 (\|v - v_p\|_{\mathcal{H},i} \|w\|_{\mathcal{H},i} + \|w - w_p\|_{\mathcal{H},i} \|v_p\|_{\mathcal{H},i}) \\ &\quad + c_{\mathcal{H},i}^2 (\|v_p - v\|_{\mathcal{H},i} \|w_p\|_{\mathcal{H},i} + \|w_p - w\|_{\mathcal{H},i} \|v\|_{\mathcal{H},i}). \end{aligned}$$

The proof is completed by writing $\|v_p\|_{\mathcal{H},i} \leq \|v_p - v\|_{\mathcal{H},i} + \|v\|_{\mathcal{H},i}$ and similarly for w_p , and taking the infimum over $v_p, w_p \in \mathcal{P}^{k_i}$. \square

As the sequences we consider in the following sections are “fully discrete” (that is, the discrete spaces are those of the degrees of freedom of the method), they are not naturally related to any polynomial functions on the computational domain. Instead, such functions are obtained through potential reconstructions. We therefore assume, for all index i , the existence of a linear map $P_i : X_i \rightarrow \mathcal{P}^{k_i}$, the norm of which (when \mathcal{P}^{k_i} is endowed with the \mathcal{L}_i -norm) is denoted by $\|P_i\|$. We then set

$$\hat{P}_i := P_i E_i : \hat{X}_i \rightarrow \mathcal{P}^{k_i}.$$

The proof of the following primal consistency result is done as the proof of Proposition 5 and is therefore omitted.

Proposition 6 (Primal consistency of potential reconstructions). *Assume (A2), (A3), and that P_i is polynomially consistent, in the sense that $P_i I_i v_p = v_p$ for all $v_p \in \mathcal{P}^{k_i}$. Then, \hat{P}_i is also polynomially consistent, in the sense that $\hat{P}_i \hat{I}_i v_p = v_p$ for all $v_p \in \mathcal{P}^{k_i}$, and we moreover have*

$$\|\hat{P}_i \hat{I}_i v - v\|_{\mathcal{L},i} \leq (\|P_i\| \|\hat{R}_i\| \|I_i\| + 1) \omega_{\mathcal{H},\mathcal{P},i}(v), \quad \forall v \in \mathcal{H}_i.$$

Commutation properties for discrete differential operators are an essential tools to design schemes that are robust with respect to physical parameters [10, 21]. They also naturally lead to optimal consistency properties. Both properties are tackled in the next proposition.

Proposition 7 (Commutation and consistency of differential operators). *Assume (C3) and that, for some unbounded operator $D_i : \mathcal{H}_i \rightarrow \mathcal{H}_{i+1}$ with domain $\text{dom}(D_i)$, the commutation property $I_{i+1} D_i = \mathfrak{d}_i I_i$ holds on $\text{dom}(D_i)$ for the top sequence. Then, it also for the bottom sequence: $\hat{I}_{i+1} D_i = \hat{\mathfrak{d}}_i \hat{I}_i$ on $\text{dom}(D_i)$.*

As a consequence, if (A2) and (A3) hold, and if the potential reconstruction P_{i+1} is polynomially consistent, then

$$\|\hat{P}_{i+1} \hat{\mathfrak{d}}_i \hat{I}_i v - D_i v\|_{\mathcal{L},i} \leq (\|P_{i+1}\| \|\hat{R}_{i+1}\| \|I_{i+1}\| + 1) \omega_{\mathcal{H},P,i+1}(D_i v) \quad \forall v \in \text{dom}(D_i). \quad (2.9)$$

Proof. We simply write

$$\hat{\mathfrak{d}}_i \hat{I}_i \stackrel{(2.4)}{=} \hat{\mathfrak{d}}_i \hat{R}_i I_i \stackrel{(C3)}{=} \hat{R}_{i+1} \mathfrak{d}_i I_i = \hat{R}_{i+1} I_{i+1} D_i \stackrel{(2.4)}{=} \hat{I}_{i+1} D_i,$$

where the third equality comes from the commutation property for the top sequence. The consistency property (2.9) then directly follows from Proposition 6. \square

Remark 8 (Consistency in non-Hilbert spaces). The primal consistency of the potential reconstruction and the discrete differential operator do not rely on the inner product of the spaces \mathcal{H} , and could therefore also be stated with non-Hilbert spaces.

Adjoint consistency error bounds are crucial to establish error estimates for numerical schemes based on non-conforming complexes. The following proposition shows that, if the top sequence satisfies an adjoint consistency estimate, then so does the bottom sequence.

Proposition 9 (Adjoint consistency). *Assume that (A2), (A3) and (C3) hold, and consider an unbounded operator $D_i^* : \mathcal{L}_{i+1} \rightarrow \mathcal{L}_i$ with domain $\text{dom}(D_i^*)$. Let $u \in \mathcal{H}_{i+1} \cap \text{dom}(D_i^*)$ and define the consistency error of the top and bottom sequences, respectively, by*

$$\begin{aligned} \mathcal{E}_i(u) &:= \sup_{x \in X_i \setminus \{0\}} \frac{(I_{i+1} u, \mathfrak{d}_i x)_{X_{i+1}} + (D_i^* u, P_i x)_{\mathcal{L},i}}{\|x\|_{X,i} + \|\mathfrak{d}_i x\|_{X_{i+1}}}, \\ \hat{\mathcal{E}}_i(u) &:= \max_{\hat{x} \in \hat{X}_i \setminus \{0\}} \frac{(\hat{I}_{i+1} u, \hat{\mathfrak{d}}_i \hat{x})_{\hat{X}_{i+1}} + (D_i^* u, \hat{P}_i \hat{x})_{\mathcal{L},i}}{\|\hat{x}\|_{\hat{X},i} + \|\hat{\mathfrak{d}}_i \hat{x}\|_{\hat{X}_{i+1}}}. \end{aligned}$$

Then, the following estimate holds:

$$\hat{\mathcal{E}}_i(u) \leq \mathcal{E}_i(u) + (\|\hat{R}_{i+1}\| + 1) \|I_{i+1}\| \omega_{\mathcal{H},\mathcal{P},i+1}(u).$$

Proof. We first notice that, for all $u_p \in \mathcal{P}^{k_{i+1}}$, $E_{i+1} \hat{I}_{i+1} u_p - I_{i+1} u_p = 0$ by (A2). Hence, inserting this quantity into the left-hand side norm below, using a triangle inequality, noticing that, since $E_{i+1} : \hat{X}_{i+1} \rightarrow X_{i+1}$ is an isometry, $\|E_{i+1} \hat{I}_{i+1} \cdot\|_{X_{i+1}} = \|\hat{R}_{i+1} I_{i+1} \cdot\|_{\hat{X}_{i+1}} \leq \|\hat{R}_{i+1}\| \|I_{i+1}\| \|\cdot\|_{X_{i+1}}$, and taking the infimum over u_p , we have

$$\begin{aligned} \|E_{i+1} \hat{I}_{i+1} u - I_{i+1} u\|_{X_{i+1}} &\leq \|E_{i+1} \hat{I}_{i+1} (u - u_p)\|_{X_{i+1}} + \|I_{i+1} (u_p - u)\|_{X_{i+1}} \\ &\leq (\|\hat{R}_{i+1}\| + 1) \|I_{i+1}\| \omega_{\mathcal{H},\mathcal{P},i+1}(u). \end{aligned} \quad (2.10)$$

Recalling (2.3), we then write, for $\hat{x} \in \hat{X}_i$,

$$\begin{aligned} (\hat{I}_{i+1}u, \hat{d}_i\hat{x})_{\hat{X}_{i+1}} &= (E_{i+1}\hat{I}_{i+1}u, E_{i+1}\hat{d}_i\hat{x})_{X_{i+1}} \\ &= (I_{i+1}u, d_i E_i \hat{x})_{X_{i+1}} + (E_{i+1}\hat{I}_{i+1}u - I_{i+1}u, d_i E_i \hat{x})_{X_{i+1}}. \end{aligned}$$

where the second line is obtained inserting $\pm I_{i+1}u$ and using the cochain map property (C3) of the extension to write $E_{i+1}\hat{d}_i\hat{x} = d_i E_i \hat{x}$. Invoking then (2.10), the definition of $\mathcal{E}_i(u)$ with $x = E_i \hat{x}$, and $P_i x = P_i E_i \hat{x} = \hat{P}_i \hat{x}$, we infer

$$\begin{aligned} (\hat{I}_{i+1}u, \hat{d}_i\hat{x})_{\hat{X}_{i+1}} + (D_i^*u, \hat{P}_i\hat{x})_{\mathcal{L},i} &\leq \mathcal{E}_i(u) (\|E_i\hat{x}\|_{X,i} + \|d_i E_i \hat{x}\|_{X,i+1}) \\ &\quad + (\|\hat{R}_{i+1}\| + 1) \|I_{i+1}\| \omega_{\mathcal{H},\mathcal{P},i+1}(u) \|d_i E_i \hat{x}\|_{X,i+1}. \end{aligned}$$

The proof is completed by noticing that, by isometry and cochain map property (C3) of the extensions, $\|E_i\hat{x}\|_{X,i} + \|d_i E_i \hat{x}\|_{X,i+1} = \|\hat{x}\|_{\hat{X},i} + \|\hat{d}_i\hat{x}\|_{\hat{X},i+1}$. \square

3 Setting

3.1 Domain and mesh

Let $\Omega \subset \mathbb{R}^3$ denote a connected polyhedral domain. We consider, as in [14], a polyhedral mesh $\mathcal{M}_h := \mathcal{T}_h \cup \mathcal{F}_h \cup \mathcal{E}_h \cup \mathcal{V}_h$, where \mathcal{T}_h gathers the elements, \mathcal{F}_h the faces, \mathcal{E}_h the edges, and \mathcal{V}_h the vertices. For all $P \in \mathcal{M}_h$, we denote by h_P its diameter and set $h := \max_{T \in \mathcal{T}_h} h_T$. For each face $F \in \mathcal{F}_h$, we fix a unit normal \mathbf{n}_F to F and, for each edge $E \in \mathcal{E}_h$, a unit tangent \mathbf{t}_E . For $T \in \mathcal{T}_h$, \mathcal{F}_T gathers the faces on the boundary ∂T of T and \mathcal{E}_T the edges in ∂T ; if $F \in \mathcal{F}_h$, \mathcal{E}_F is the set of edges contained in the boundary ∂F of F . For $F \in \mathcal{F}_h$, $\omega_{TF} \in \{-1, +1\}$ is such that $\omega_{TF} \mathbf{n}_F$ is the outer normal on F to T .

Each face $F \in \mathcal{F}_h$ is oriented counter-clockwise with respect to \mathbf{n}_F and, for $E \in \mathcal{E}_F$, we let $\omega_{FE} \in \{-1, +1\}$ be such that $\omega_{FE} = +1$ if \mathbf{t}_E points along the boundary ∂F of F in the clockwise sense, and $\omega_{FE} = -1$ otherwise; we also denote by \mathbf{n}_{FE} the unit normal vector to E , in the plane spanned by F , such that $(\mathbf{t}_E, \mathbf{n}_{FE}, \mathbf{n}_F)$ is a right-handed system of coordinate (so that, in particular, $\omega_{FE} \mathbf{n}_{FE}$ points outside F). We denote by \mathbf{grad}_F and div_F the tangent gradient and divergence operators acting on smooth enough functions. Moreover, for any $r : F \rightarrow \mathbb{R}$ and $\mathbf{z} : F \rightarrow \mathbb{R}^2$ smooth enough, we let $\mathbf{rot}_F r := (\mathbf{grad}_F r)^\perp$ and $\mathbf{rot}_F \mathbf{z} = \text{div}_F(\mathbf{z}^\perp)$, with \perp denoting the rotation of angle $-\frac{\pi}{2}$ in the oriented tangent space to F .

We further assume that $(\mathcal{T}_h, \mathcal{F}_h)$ belongs to a regular mesh sequence as per [16, Definition 1.9], with mesh regularity parameter $\varrho > 0$. This assumption ensures the existence, for each $P \in \mathcal{T}_h \cup \mathcal{F}_h \cup \mathcal{E}_h$, of a point $\mathbf{x}_P \in P$ such that the ball centered at \mathbf{x}_P and of radius ϱh_P is contained in P .

3.2 Polynomial spaces and L^2 -orthogonal projectors

For any $P \in \mathcal{M}_h$ and an integer $\ell \geq 0$, we denote by $\mathcal{P}^\ell(P)$ the space spanned by the restriction to P of polynomial functions of the space variables. Letting $\mathcal{P}^\ell(P) := \mathcal{P}^\ell(P)^n$ for $P \in \mathcal{T}_h$ and $n = 3$ or $P \in \mathcal{F}_h$ and $n = 2$, it holds: For all $F \in \mathcal{F}_h$,

$$\begin{aligned} \mathcal{P}^\ell(F) &= \mathcal{G}^\ell(F) \oplus \mathcal{G}^{c,\ell}(F) \quad \text{with } \mathcal{G}^\ell(F) := \mathbf{grad}_F \mathcal{P}^{\ell+1}(F) \text{ and } \mathcal{G}^{c,\ell}(F) := (\mathbf{x} - \mathbf{x}_F)^\perp \mathcal{P}^{\ell-1}(F) \\ &= \mathcal{R}^\ell(F) \oplus \mathcal{R}^{c,\ell}(F) \quad \text{with } \mathcal{R}^\ell(F) := \mathbf{rot}_F \mathcal{P}^{\ell+1}(F) \text{ and } \mathcal{R}^{c,\ell}(F) := (\mathbf{x} - \mathbf{x}_F) \mathcal{P}^{\ell-1}(F) \end{aligned}$$

and, for all $T \in \mathcal{T}_h$,

$$\mathcal{P}^\ell(T) = \mathcal{G}^\ell(T) \oplus \mathcal{G}^{c,\ell}(T) \quad \text{with } \mathcal{G}^\ell(T) := \mathbf{grad} \mathcal{P}^{\ell+1}(T) \text{ and } \mathcal{G}^{c,\ell}(T) := (\mathbf{x} - \mathbf{x}_T) \times \mathcal{P}^{\ell-1}(T) \quad (3.1)$$

$$= \mathcal{R}^\ell(T) \oplus \mathcal{R}^{c,\ell}(T) \quad \text{with } \mathcal{R}^\ell(T) := \mathbf{curl} \mathcal{P}^{\ell+1}(T) \text{ and } \mathcal{R}^{c,\ell}(T) := (\mathbf{x} - \mathbf{x}_T) \mathcal{P}^{\ell-1}(T). \quad (3.2)$$

We extend the above notations to negative exponents ℓ by setting all the spaces appearing in the decompositions equal to the trivial vector space $\{\mathbf{0}\}$. Given a polynomial (sub)space $\mathcal{X}^\ell(P)$ on $P \in \mathcal{M}_h$,

the corresponding L^2 -orthogonal projector is denoted by $\pi_{\mathcal{X},\mathbf{P}}^\ell$. Boldface font will be used when the elements of $\mathcal{X}^\ell(\mathbf{P})$ are vector-valued. The spaces in the above decompositions are hierarchical, i.e., for all $\mathcal{X} \in \{\mathcal{G}, \mathcal{R}\}$ and all $\mathbf{P} \in \mathcal{T}_h \cup \mathcal{F}_h$, $\mathcal{X}^{\ell-1}(\mathbf{P}) \subset \mathcal{X}^\ell(\mathbf{P})$. In what follows, we will frequently use this property to write, for all integers $\ell \leq k-1$ and $\mathbf{P} \in \mathcal{T}_h \cup \mathcal{F}_h$,

$$\boldsymbol{\pi}_{\mathcal{X},\mathbf{P}}^{c,\ell+1} \boldsymbol{\pi}_{\mathcal{X},\mathbf{P}}^{c,k} = \boldsymbol{\pi}_{\mathcal{X},\mathbf{P}}^{c,\ell+1}. \quad (3.3)$$

4 DDR complex

In this section we briefly recall the DDR complex and refer to [14, Section 3] for further details. From this point on, we fix an integer $k \geq 0$ corresponding to the polynomial degree of the complex.

4.1 Spaces and component norms

The DDR counterparts of $H^1(\Omega)$, $\mathbf{H}(\mathbf{curl}; \Omega)$, $\mathbf{H}(\mathbf{div}; \Omega)$ and $L^2(\Omega)$ are respectively defined as follows:

$$\begin{aligned} \underline{\mathbf{X}}_{\mathbf{grad},h}^k &:= \left\{ \underline{q}_h = ((q_T)_{T \in \mathcal{T}_h}, (q_F)_{F \in \mathcal{F}_h}, q_{\mathcal{E}_h}) : \right. \\ &\quad \left. q_T \in \mathcal{P}^{k-1}(T) \text{ for all } T \in \mathcal{T}_h, q_F \in \mathcal{P}^{k-1}(F) \text{ for all } F \in \mathcal{F}_h, \text{ and } q_{\mathcal{E}_h} \in \mathcal{P}_c^{k+1}(\mathcal{E}_h) \right\}, \end{aligned}$$

with $\mathcal{P}_c^{k+1}(\mathcal{E}_h)$ denoting the space of functions that are continuous on the mesh edge skeleton and the restriction of which to each $E \in \mathcal{E}_h$ belongs to $\mathcal{P}^{k+1}(E)$,

$$\begin{aligned} \underline{\mathbf{X}}_{\mathbf{curl},h}^k &:= \left\{ \underline{v}_h = ((\mathbf{v}_{\mathcal{R},T}, \mathbf{v}_{\mathcal{R},T}^c)_{T \in \mathcal{T}_h}, (\mathbf{v}_{\mathcal{R},F}, \mathbf{v}_{\mathcal{R},F}^c)_{F \in \mathcal{F}_h}, (v_E)_{E \in \mathcal{E}_h}) : \right. \\ &\quad \mathbf{v}_{\mathcal{R},T} \in \mathcal{R}^{k-1}(T) \text{ and } \mathbf{v}_{\mathcal{R},T}^c \in \mathcal{R}^{c,k}(T) \text{ for all } T \in \mathcal{T}_h, \\ &\quad \mathbf{v}_{\mathcal{R},F} \in \mathcal{R}^{k-1}(F) \text{ and } \mathbf{v}_{\mathcal{R},F}^c \in \mathcal{R}^{c,k}(F) \text{ for all } F \in \mathcal{F}_h, \\ &\quad \left. \text{and } v_E \in \mathcal{P}^k(E) \text{ for all } E \in \mathcal{E}_h \right\}, \end{aligned}$$

$$\begin{aligned} \underline{\mathbf{X}}_{\mathbf{div},h}^k &:= \left\{ \underline{w}_h = ((\mathbf{w}_{\mathcal{G},T}, \mathbf{w}_{\mathcal{G},T}^c)_{T \in \mathcal{T}_h}, (w_F)_{F \in \mathcal{F}_h}) : \right. \\ &\quad \mathbf{w}_{\mathcal{G},T} \in \mathcal{G}^{k-1}(T) \text{ and } \mathbf{w}_{\mathcal{G},T}^c \in \mathcal{G}^{c,k}(T) \text{ for all } T \in \mathcal{T}_h, \\ &\quad \left. \text{and } w_F \in \mathcal{P}^k(F) \text{ for all } F \in \mathcal{F}_h \right\}, \end{aligned} \quad (4.1)$$

and

$$\mathcal{P}^k(\mathcal{T}_h) := \{q_h \in L^2(\Omega) : (q_h)|_T \in \mathcal{P}^k(T) \text{ for all } T \in \mathcal{T}_h\}.$$

The corresponding interpolators are denoted by $\underline{\mathbf{I}}_{\mathbf{grad},h}^k$, $\underline{\mathbf{I}}_{\mathbf{curl},h}^k$, $\underline{\mathbf{I}}_{\mathbf{div},h}^k$, and $\pi_{\mathcal{P},h}^k$. The interpolator on $\underline{\mathbf{X}}_{\mathbf{grad},h}^k$ is defined by (4.9) below, while the remaining interpolators correspond to the L^2 -projections on the polynomial spaces appearing in the definitions of $\underline{\mathbf{X}}_{\mathbf{curl},h}^k$, $\underline{\mathbf{X}}_{\mathbf{div},h}^k$, and $\mathcal{P}^k(\mathcal{T}_h)$, respectively; see [14] for details. The restriction of each of these spaces to a mesh entity $\mathbf{P} \in \mathcal{M}_h$ that appears in its definition gathers the polynomial components on \mathbf{P} and the geometric entities on its boundary, and is denoted replacing the subscript h by \mathbf{P} . A similar convention is used for the elements of such restrictions as well as for the interpolators.

From this point on, to alleviate the notation, for all $\mathbf{P} \in \{\Omega\} \cup \mathcal{T}_h \cup \mathcal{F}_h \cup \mathcal{E}_h$, we denote by $\|\cdot\|_{\mathbf{P}}$ the standard $L^2(\mathbf{P})$ -norm. The same notation is used for the norm of $L^2(\mathbf{P})^n$ (with n denoting the dimension of \mathbf{P}), any ambiguity being removed by the scalar or vector nature of the argument. In the analysis, we will additionally make use of the following local component L^2 -norms $\|\cdot\|_{\bullet,\mathbf{P}} : \underline{\mathbf{X}}_{\bullet,\mathbf{P}}^k \rightarrow \mathbb{R}$,

for $\bullet \in \{\mathbf{grad}, \mathbf{curl}, \mathbf{div}\}$ and $\mathbf{P} \in \mathcal{T}_h \cup \mathcal{F}_h$ (only $\mathbf{P} \in \mathcal{F}_h$ if $\bullet = \mathbf{div}$):

$$\begin{aligned}
\| \underline{q}_F \|_{\mathbf{grad}, F} &:= \left(\|q_F\|_F^2 + \sum_{E \in \mathcal{E}_F} h_E \|q_E\|_E^2 \right)^{1/2} & \forall F \in \mathcal{F}_h, \forall \underline{q}_F \in \underline{X}_{\mathbf{grad}, F}^k, \\
\| \underline{q}_T \|_{\mathbf{grad}, T} &:= \left(\|q_T\|_T^2 + \sum_{F \in \mathcal{F}_T} h_F \| \underline{q}_F \|_{\mathbf{grad}, F}^2 \right)^{1/2} & \forall T \in \mathcal{T}_h, \forall \underline{q}_T \in \underline{X}_{\mathbf{grad}, T}^k, \\
\| \underline{v}_F \|_{\mathbf{curl}, F} &:= \left(\|v_{\mathcal{R}, F}\|_F^2 + \|v_{\mathcal{R}, F}^c\|_F^2 + \sum_{E \in \mathcal{E}_F} h_E \|v_E\|_E^2 \right)^{1/2} & \forall F \in \mathcal{F}_h, \forall \underline{v}_F \in \underline{X}_{\mathbf{curl}, F}^k, \quad (4.2) \\
\| \underline{v}_T \|_{\mathbf{curl}, T} &:= \left(\|v_{\mathcal{R}, T}\|_T^2 + \|v_{\mathcal{R}, T}^c\|_T^2 + \sum_{F \in \mathcal{F}_T} h_F \| \underline{v}_F \|_{\mathbf{curl}, F}^2 \right)^{1/2} & \forall T \in \mathcal{F}_h, \forall \underline{v}_T \in \underline{X}_{\mathbf{curl}, T}^k, \\
\| \underline{w}_T \|_{\mathbf{div}, T} &:= \left(\|w_{\mathcal{G}, T}\|_T^2 + \|w_{\mathcal{G}, T}^c\|_T^2 + \sum_{F \in \mathcal{F}_T} h_F \|w_F\|_F^2 \right)^{1/2} & \forall T \in \mathcal{T}_h, \forall \underline{w}_T \in \underline{X}_{\mathbf{div}, T}^k.
\end{aligned}$$

For $\bullet \in \{\mathbf{grad}, \mathbf{curl}, \mathbf{div}\}$, a global component L^2 -norm is obtained setting $\| \cdot \|_{\bullet, h} := \left(\sum_{T \in \mathcal{T}_h} \| \cdot \|_{\bullet, T}^2 \right)^{1/2}$.

4.2 Discrete vector calculus operators and potentials

4.2.1 Gradient

For any $E \in \mathcal{E}_h$, the edge gradient $G_E^k : \underline{X}_{\mathbf{grad}, E}^k \rightarrow \mathcal{P}^k(E)$ is such that, for all $q_E \in \underline{X}_{\mathbf{grad}, E}^k$, $G_E^k q_E = q'_E$, where q_E denotes the restriction to E of $q_{\mathcal{E}_h}$ and the derivative is taken in the direction \mathbf{t}_E .

For any $F \in \mathcal{F}_h$, the face gradient $\mathbf{G}_F^k : \underline{X}_{\mathbf{grad}, F}^k \rightarrow \mathcal{P}^k(F)$ and the scalar trace $\gamma_F^{k+1} : \underline{X}_{\mathbf{grad}, F}^k \rightarrow \mathcal{P}^{k+1}(F)$ are such that, for all $\underline{q}_F \in \underline{X}_{\mathbf{grad}, F}^k$,

$$\begin{aligned}
\int_F \mathbf{G}_F^k \underline{q}_F \cdot \mathbf{v}_F &= - \int_F q_F \operatorname{div}_F \mathbf{v}_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E q_E (\mathbf{v}_F \cdot \mathbf{n}_{FE}) & \forall \mathbf{v}_F \in \mathcal{P}^k(F), \quad (4.3) \\
\int_F \gamma_F^{k+1} \underline{q}_F \operatorname{div}_F \mathbf{v}_F &= - \int_F \mathbf{G}_F^k \underline{q}_F \cdot \mathbf{v}_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \gamma_E^{k+1} \underline{q}_E (\mathbf{v}_F \cdot \mathbf{n}_{FE}) & \forall \mathbf{v}_F \in \mathcal{R}^{c, k+2}(F).
\end{aligned}$$

Similarly, for all $T \in \mathcal{T}_h$, the element gradient $\mathbf{G}_T^k : \underline{X}_{\mathbf{grad}, T}^k \rightarrow \mathcal{P}^k(T)$ and the scalar potential $P_{\mathbf{grad}, T}^{k+1} : \underline{X}_{\mathbf{grad}, T}^k \rightarrow \mathcal{P}^{k+1}(T)$ are defined such that, for all $\underline{q}_T \in \underline{X}_{\mathbf{grad}, T}^k$,

$$\begin{aligned}
\int_T \mathbf{G}_T^k \underline{q}_T \cdot \mathbf{v}_T &= - \int_T q_T \operatorname{div} \mathbf{v}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{q}_F (\mathbf{v}_T \cdot \mathbf{n}_F) & \forall \mathbf{v}_T \in \mathcal{P}^k(T), \quad (4.4) \\
\int_T P_{\mathbf{grad}, T}^{k+1} \underline{q}_T \operatorname{div} \mathbf{v}_T &= - \int_T \mathbf{G}_T^k \underline{q}_T \cdot \mathbf{v}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{q}_F (\mathbf{v}_T \cdot \mathbf{n}_F) & \forall \mathbf{v}_T \in \mathcal{R}^{c, k+2}(T).
\end{aligned}$$

For future use, we notice that, using discrete inverse and trace inequalities and, for mesh elements, the continuity of γ_F^{k+1} stated in [14, Proposition 6], it holds, for all $\mathbf{P} \in \mathcal{T}_h \cup \mathcal{F}_h$,

$$\| \mathbf{G}_{\mathbf{P}}^k \underline{q}_{\mathbf{P}} \|_{\mathbf{P}} \lesssim h_{\mathbf{P}}^{-1} \| \underline{q}_{\mathbf{P}} \|_{\mathbf{grad}, \mathbf{P}} \quad \forall \underline{q}_{\mathbf{P}} \in \underline{X}_{\mathbf{grad}, \mathbf{P}}^k. \quad (4.5)$$

4.2.2 Curl

For all $F \in \mathcal{F}_h$, the face curl $\mathbf{C}_F^k : \underline{\mathbf{X}}_{\text{curl},F}^k \rightarrow \mathcal{P}^k(F)$ and the corresponding vector potential (which can be interpreted as a tangential component) $\boldsymbol{\gamma}_{\mathbf{t},F}^k : \underline{\mathbf{X}}_{\text{curl},F}^k \rightarrow \mathcal{P}^k(F)$ are such that, for all $\underline{\mathbf{v}}_F \in \underline{\mathbf{X}}_{\text{curl},F}^k$,

$$\int_F \mathbf{C}_F^k \underline{\mathbf{v}}_F \cdot \mathbf{r}_F = \int_F \mathbf{v}_{\mathcal{R},F} \cdot \mathbf{rot}_F \mathbf{r}_F - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \mathbf{v}_E \cdot \mathbf{r}_F \quad \forall \mathbf{r}_F \in \mathcal{P}^k(F) \quad (4.6)$$

and, for all $(\mathbf{r}_F, \mathbf{w}_F) \in \mathcal{P}^{0,k+1}(F) \times \mathcal{R}^{c,k}(F)$,

$$\int_F \boldsymbol{\gamma}_{\mathbf{t},F}^k \underline{\mathbf{v}}_F \cdot (\mathbf{rot}_F \mathbf{r}_F + \mathbf{w}_F) = \int_F \mathbf{C}_F^k \underline{\mathbf{v}}_F \cdot \mathbf{r}_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \mathbf{v}_E \cdot \mathbf{r}_F + \int_F \mathbf{v}_{\mathcal{R},F}^c \cdot \mathbf{w}_F.$$

For all $T \in \mathcal{T}_h$, the element curl $\mathbf{C}_T^k : \underline{\mathbf{X}}_{\text{curl},T}^k \rightarrow \mathcal{P}^k(T)$ and the vector potential $\mathbf{P}_{\text{curl},T}^k : \underline{\mathbf{X}}_{\text{curl},T}^k \rightarrow \mathcal{P}^k(T)$ are defined such that, for all $\underline{\mathbf{v}}_T \in \underline{\mathbf{X}}_{\text{curl},T}^k$,

$$\int_T \mathbf{C}_T^k \underline{\mathbf{v}}_T \cdot \mathbf{w}_T = \int_T \mathbf{v}_{\mathcal{R},T} \cdot \mathbf{curl} \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \boldsymbol{\gamma}_{\mathbf{t},F}^k \underline{\mathbf{v}}_F \cdot (\mathbf{w}_T \times \mathbf{n}_F) \quad \forall \mathbf{w}_T \in \mathcal{P}^k(T) \quad (4.7)$$

and, for all $(\mathbf{w}_T, \mathbf{z}_T) \in \mathcal{G}^{c,k+1}(T) \times \mathcal{R}^{c,k}(T)$,

$$\int_T \mathbf{P}_{\text{curl},T}^k \underline{\mathbf{v}}_T \cdot (\mathbf{curl} \mathbf{w}_T + \mathbf{z}_T) = \int_T \mathbf{C}_T^k \underline{\mathbf{v}}_T \cdot \mathbf{w}_T - \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \boldsymbol{\gamma}_{\mathbf{t},F}^k \underline{\mathbf{v}}_F \cdot (\mathbf{w}_T \times \mathbf{n}_F) + \int_T \mathbf{v}_{\mathcal{R},T}^c \cdot \mathbf{z}_T.$$

4.2.3 Divergence

For all $T \in \mathcal{T}_h$, the element divergence $D_T^k : \underline{\mathbf{X}}_{\text{div},T}^k \rightarrow \mathcal{P}^k(T)$ and vector potential $\mathbf{P}_{\text{div},T}^k : \underline{\mathbf{X}}_{\text{div},T}^k \rightarrow \mathcal{P}^k(T)$ are defined by: For all $\underline{\mathbf{w}}_T \in \underline{\mathbf{X}}_{\text{div},T}^k$,

$$\int_T D_T^k \underline{\mathbf{w}}_T \cdot \mathbf{q}_T = - \int_T \mathbf{w}_{\mathcal{G},T} \cdot \mathbf{grad} \mathbf{q}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \mathbf{w}_F \cdot \mathbf{q}_T \quad \forall \mathbf{q}_T \in \mathcal{P}^k(T) \quad (4.8)$$

and, for all $(\mathbf{r}_T, \mathbf{z}_T) \in \mathcal{P}^{0,k+1}(T) \times \mathcal{G}^{c,k}(T)$,

$$\int_T \mathbf{P}_{\text{div},T}^k \underline{\mathbf{w}}_T \cdot (\mathbf{grad} \mathbf{r}_T + \mathbf{z}_T) = - \int_T D_T^k \underline{\mathbf{w}}_T \cdot \mathbf{r}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \mathbf{w}_F \cdot \mathbf{r}_T + \int_T \mathbf{w}_{\mathcal{G},T}^c \cdot \mathbf{z}_T.$$

4.3 DDR complex

The DDR complex reads:

$$\mathbb{R} \xrightarrow{I_{\text{grad},h}^k} \underline{\mathbf{X}}_{\text{grad},h}^k \xrightarrow{\mathbf{G}_h^k} \underline{\mathbf{X}}_{\text{curl},h}^k \xrightarrow{\mathbf{C}_h^k} \underline{\mathbf{X}}_{\text{div},h}^k \xrightarrow{D_h^k} \mathcal{P}^k(\mathcal{T}_h) \xrightarrow{0} \{0\},$$

where the interpolator on $\underline{\mathbf{X}}_{\text{grad},h}^k$ is such that, for all $q : \Omega \rightarrow \mathbb{R}$ smooth enough,

$$\begin{aligned} I_{\text{grad},h}^k q &:= ((\pi_{\mathcal{P},T}^{k-1} q|_T)_{T \in \mathcal{T}_h}, (\pi_{\mathcal{P},F}^{k-1} q|_F)_{F \in \mathcal{F}_h}, q_{\mathcal{E}_h}), \text{ with } q_{\mathcal{E}_h} \in \mathcal{P}_c^{k+1}(\mathcal{E}_h) \text{ such that} \\ q_{\mathcal{E}_h}(\mathbf{x}_V) &= q(\mathbf{x}_V) \text{ for all } V \in \mathcal{V}_h \text{ and } \pi_{\mathcal{P},E}^{k-1} q_E = \pi_{\mathcal{P},E}^{k-1} q \text{ for all } E \in \mathcal{E}_h. \end{aligned} \quad (4.9)$$

and the global discrete gradient, curl, and divergence operators are such that, for all $(\underline{q}_h, \underline{\mathbf{v}}_h, \underline{\mathbf{w}}_h) \in \underline{\mathbf{X}}_{\text{grad},h}^k \times \underline{\mathbf{X}}_{\text{curl},h}^k \times \underline{\mathbf{X}}_{\text{div},h}^k$,

$$\begin{aligned} \mathbf{G}_h^k \underline{q}_h &:= ((\pi_{\mathcal{R},T}^{k-1} \mathbf{G}_T^k \underline{q}_T, \pi_{\mathcal{R},T}^{c,k} \mathbf{G}_T^{c,k} \underline{q}_T)_{T \in \mathcal{T}_h}, (\pi_{\mathcal{R},F}^{k-1} \mathbf{G}_F^k \underline{q}_F, \pi_{\mathcal{R},F}^{c,k} \mathbf{G}_F^{c,k} \underline{q}_F)_{F \in \mathcal{F}_h}, (G_E^k q_E)_{E \in \mathcal{E}_h}), \\ \mathbf{C}_h^k \underline{\mathbf{v}}_h &:= ((\pi_{\mathcal{G},T}^{k-1} \mathbf{C}_T^k \underline{\mathbf{v}}_T, \pi_{\mathcal{G},T}^{c,k} \mathbf{C}_T^{c,k} \underline{\mathbf{v}}_T)_{T \in \mathcal{T}_h}, (\mathbf{C}_F^k \underline{\mathbf{v}}_F)_{F \in \mathcal{F}_h}), \\ (D_h^k \underline{\mathbf{w}}_h)|_T &:= D_T^k \underline{\mathbf{w}}_T \quad \forall T \in \mathcal{T}_h. \end{aligned}$$

4.4 Discrete L^2 -products and norms

For $\bullet \in \{\mathbf{grad}, \mathbf{curl}, \mathbf{div}\}$, we define a discrete L^2 -product on $\underline{X}_{\bullet,h}^k$ setting, for all $\underline{x}_h, \underline{y}_h \in \underline{X}_{\bullet,h}^k$,

$$(\underline{x}_h, \underline{y}_h)_{\bullet,h} := \sum_{T \in \mathcal{T}_h} (\underline{x}_T, \underline{y}_T)_{\bullet,T},$$

with local contribution such that, denoting by $P_{\bullet,T}^l$ the potential on $\underline{X}_{\bullet,T}^k$ (with $l = k + 1$ if $\bullet = \mathbf{grad}$, $l = k$ otherwise),

$$(\underline{x}_T, \underline{y}_T)_{\bullet,T} := \int_T P_{\bullet,T}^l \underline{x}_T \cdot P_{\bullet,T}^l \underline{y}_T + s_{\bullet,T}(\underline{x}_T, \underline{y}_T).$$

Above, $s_{\bullet,T} : \underline{X}_{\bullet,T}^k \times \underline{X}_{\bullet,T}^k \rightarrow \mathbb{R}$ is a local stabilisation bilinear form, the precise expression of which can be found in [14, Section 4.4]. We will also need, in what follows, the discrete global and local L^2 -norms induced by the above L^2 -products, that will be denoted by $\|\cdot\|_{\bullet,h}$ and $\|\cdot\|_{\bullet,T}$, respectively.

5 Serendipity DDR complex

As demonstrated by the example of the DDR complex, polytopal discrete complexes have degrees of freedom (DOFs) attached to mesh entities of various dimensions: elements, faces, edges, vertices. Their specific choice is related to the degree of their polynomial consistency. The principle for constructing a serendipity version is to notice that, on a polygonal face (resp. polyhedral element), the knowledge of a polynomial on the boundary alone can often provide sufficient information to reconstruct it inside the face (resp. element).

Following the notations of Section 2, this principle guides the construction of the serendipity spaces \hat{X}_i , in which face or element internal DOFs that are not required to reconstruct polynomials of the desired degree are removed. The reduction map \hat{R} consists in removing these DOFs, while the extension map E re-creates these DOFs by fixing them to those of the polynomial reconstructed from the boundary and remaining internal DOFs; this way, DOFs representing in X_i (through I_i) polynomials in \mathcal{P}^{k_i} are exactly recovered, ensuring the polynomial consistency expressed by (A2), which is a driving property in the process.

This design, however, has a caveat, as the DOFs removed on a lower-dimensional entity (e.g., a face) can impact some components of the discrete differential operators on higher-dimensional entities (e.g., an element); in particular, to ensure the cochain map property (C3), the values of the reduction operator attached to higher-dimensional entities might have to be adjusted to account for the removal of DOFs on lower-dimensional entities. The design of the reduction operator is thus initially inspired by the consistency property, but must then be tuned to fulfill Assumption 1, which relates to the choice of serendipity spaces in each vertical section of Diagram (2.1).

The rest of this section shows how to apply these principles to the DDR sequence presented in [10, 14]. In this context, focusing on the local sequence on an element T of the mesh, Diagram (2.1) becomes Diagram (5.1) below. The operators that appear in the construction of the SDDR complex are summarized in Table 1.

Notation	Name	Definition
$S_{\text{grad},F}^k$	Gradient serendipity operator on faces	Problem (5.5) with \mathcal{L}_F given by (5.14)
$S_{\text{curl},F}^k$	Curl serendipity operator on faces	Problem (5.5) with \mathcal{L}_F given by (5.16)
$\underline{E}_{\text{grad},F}$	Gradient extension on faces	Eq. (5.18)
$\underline{E}_{\text{curl},F}$	Curl extension on faces	Eq. (5.19)
$\hat{R}_{\text{grad},F}$	Gradient restriction on faces	Eq. (5.23)
$\hat{R}_{\text{curl},F}$	Curl restriction on faces	Eq. (5.24)
$S_{\text{grad},T}^k$	Gradient serendipity operator on elements	Problem (5.26) with \mathcal{L}_T given by (5.28)
$S_{\text{curl},T}^k$	Curl serendipity operator on elements	Problem (5.26) with \mathcal{L}_T given by (5.30)
$\underline{E}_{\text{grad},T}$	Gradient extension on elements	Eq. (5.32)
$\underline{E}_{\text{curl},T}$	Curl extension on elements	Eq. (5.33)
$\hat{R}_{\text{grad},T}$	Gradient restriction on elements	Eq. (5.35)
$\hat{R}_{\text{curl},T}$	Curl restriction on elements	Eq. (5.36)

Table 1: Synoptic table of the operators appearing in the construction of the SDDR complex.

$$\begin{array}{ccccccc}
& \mathcal{P}^{k+1}(T) & & \mathcal{P}^k(T) & & \mathcal{P}^k(T) & & \mathcal{P}^k(T) & & \\
& \downarrow I_{\text{grad},T}^k & & \downarrow I_{\text{curl},T}^k & & \downarrow I_{\text{div},T}^k & & \downarrow \text{Id} & & \\
\mathbb{R} & \xrightarrow{I_{\text{grad},T}^k} & \underline{X}_{\text{grad},T}^k & \xrightarrow{\underline{G}_T^k} & \underline{X}_{\text{curl},T}^k & \xrightarrow{\underline{C}_T^k} & \underline{X}_{\text{div},T}^k & \xrightarrow{D_T^k} & \mathcal{P}^k(T) & \longrightarrow & 0 \\
& \uparrow \text{Id} & \uparrow \underline{E}_{\text{grad},T} & \uparrow \hat{R}_{\text{grad},T} & \uparrow \underline{E}_{\text{curl},T} & \uparrow \hat{R}_{\text{curl},T} & \uparrow \text{Id} & \uparrow \text{Id} & & & (5.1) \\
\mathbb{R} & \xrightarrow{I_{\text{grad},T}^k} & \hat{X}_{\text{grad},T}^k & \xrightarrow{\hat{G}_T^k} & \hat{X}_{\text{curl},T}^k & \xrightarrow{\hat{C}_T^k} & \hat{X}_{\text{div},T}^k & \xrightarrow{D_T^k} & \mathcal{P}^k(T) & \longrightarrow & 0
\end{array}$$

Remark 10 (No serendipity for $\underline{X}_{\text{div},T}^k$ spaces). Notice that no serendipity is performed on the space $\underline{X}_{\text{div},T}^k$. The strong objection to reducing the DOFs in that space is discussed in Section 6.5.

The global complexes are obtained collecting the local components of the spaces and operators and enforcing their single-valuedness on vertices, edges, and faces internal to the domain. For the global complex, the polynomial consistency property is not relevant. A comparison in terms of DOFs count for tetrahedral and hexahedral elements among SDDR, DDR, and (non-serendipity) finite elements is provided in Table 2.

5.1 Boundary selection and notation for inequalities

As discussed above, designing serendipity versions of the DDR spaces requires to reconstruct polynomials inside elements/faces from boundary values on selected faces/edges. To ensure a stable reconstruction, the selection of these faces/edges must be done in such a way that they are not close to being aligned. This is stated more precisely in the following assumption.

Assumption 11 (Boundaries selection for serendipity spaces). For each P element (resp. face) of the mesh, we select a set $\mathcal{B}_{s,P}$ of $\eta_P \geq 2$ faces (resp. edges) that are not pairwise aligned and such that P

Discrete space	Tetrahedron			Hexahedron		
	$k = 0$	$k = 1$	$k = 2$	$k = 0$	$k = 1$	$k = 2$
$H^1(T)$	$4 \diamond 4 \diamond 4$	$15 \diamond 10 \diamond 10$	$32 \diamond 20 \diamond 20$	$8 \diamond 8 \diamond 8$	$27 \diamond 20 \diamond 27$	$54 \diamond 32 \diamond 64$
$\mathbf{H}(\mathbf{curl}; T)$	$6 \diamond 6 \diamond 6$	$28 \diamond 23 \diamond 20$	$65 \diamond 53 \diamond 45$	$12 \diamond 12 \diamond 12$	$46 \diamond 39 \diamond 54$	$99 \diamond 77 \diamond 144$
$\mathbf{H}(\mathbf{div}; T)$	$4 \diamond 4 \diamond 4$	$18 \diamond 18 \diamond 15$	$44 \diamond 44 \diamond 36$	$6 \diamond 6 \diamond 6$	$24 \diamond 24 \diamond 36$	$56 \diamond 56 \diamond 108$
$L^2(T)$	$1 \diamond 1 \diamond 1$	$4 \diamond 4 \diamond 4$	$10 \diamond 10 \diamond 10$	$1 \diamond 1 \diamond 1$	$4 \diamond 4 \diamond 8$	$10 \diamond 10 \diamond 27$

Table 2: Dimension of the local spaces in the DDR \diamond SDDR \diamond Raviart–Thomas–Nédélec FEM discrete Hilbert complexes of comparable degree $k \in \{0, 1, 2\}$ on a tetrahedron ($\eta_T = 4$ and $\eta_F = 3$ for all $F \in \mathcal{F}_T$) and hexahedron ($\eta_T = 6$ and $\eta_F = 4$ for all $F \in \mathcal{F}_T$).

lies entirely on one side of the hyperplane H_b spanned by each $\mathbf{b} \in \mathcal{B}_{s,P}$. The scaled distance function to H_b is defined by $\text{dist}_{Pb}(\mathbf{x}) = h_P^{-1}(\mathbf{x} - \mathbf{x}_b) \cdot \mathbf{n}_{Pb}$, with \mathbf{n}_{Pb} outer normal to P on b . Finally, we define a *boundaries selection regularity parameter* $\theta > 0$ such that $\text{dist}_{Pb}(\mathbf{x}_{b'}) \geq \theta$ for all $b \neq b'$ in $\mathcal{B}_{s,P}$.

From this point on, $a \lesssim b$ (resp., $a \gtrsim b$) means $a \leq Cb$ (resp. $a \geq Cb$) with C only depending on Ω , k , the mesh regularity parameter ϱ (cf. Section 3.1), and the boundaries selection regularity parameter θ . We also write $a \simeq b$ as a shorthand for “ $a \lesssim b$ and $b \lesssim a$ ”.

Remark 12 (Trivial boundaries selection). We can always select two faces (resp. edges) in each element (resp. face) such that $\theta \gtrsim \varrho$. This minimal selection corresponds to the absence of serendipity, as can be easily verified by noticing that, in this case, (5.4) and (5.25) below give $\ell_P = k - 1$ for $P \in \mathcal{T}_h \cup \mathcal{F}_h$.

5.2 Estimates of polynomials from boundary values

We state in this section some bounds of polynomial functions on polytopes in terms of boundary values and, possibly, reduced projections in the interior of the polytope. Similar estimates have been established in the recent preprint [11], but only for 2D convex polygons and with a proof by contradiction that, contrary to the one developed in Appendix A, does not allow for a direct estimate of the constants.

Lemma 13 (Estimate of scalar polynomials from boundary values). *Let $k \geq 0$ and let Assumption 11 hold. Let $P \in \mathcal{T}_h \cup \mathcal{F}_h$ be a mesh element or face. Then, it holds*

$$\|q\|_P \lesssim \|\pi_{\mathcal{P},P}^{k+1-\eta_P} q\|_P + h_P^{\frac{1}{2}} \sum_{b \in \mathcal{B}_{s,P}} \|q|_b\|_b \quad \forall q \in \mathcal{P}^{k+1}(P). \quad (5.2)$$

Proof. See Section A.1. □

Lemma 14 (Estimate of vector polynomials from tangential boundary values). *Let $k \geq 0$ and let Assumption 11 hold. Let $P \in \mathcal{T}_h \cup \mathcal{F}_h$ be a mesh element or face. Then, denoting by \mathcal{B}_P the set of faces (if P is an element) or edges (if P is a face) of P , it holds*

$$\|\mathbf{v}\|_P \lesssim \|\pi_{\mathcal{R},P}^{k-2} \mathbf{v}\|_P + \|\pi_{\mathcal{R},P}^{c,k+2-\eta_P} \mathbf{v}\|_P + \left(\sum_{b \in \mathcal{B}_P} h_P \|v_{t,b}\|_b^2 \right)^{1/2} \quad \forall \mathbf{v} \in \mathcal{P}^k(P), \quad (5.3)$$

where $v_{t,b}$ is the tangential component of \mathbf{v} on b (that is, $v_{t,b} = \mathbf{v}|_E \cdot \mathbf{t}_E$ if $b = E$ is an edge, $v_{t,b} = \mathbf{n}_F \times (\mathbf{v}|_F \times \mathbf{n}_F)$ if $b = F$ is a face).

Proof. See Section A.2. □

5.3 Serendipity, extension, and reduction operators on faces

5.3.1 Serendipity problem

For a face $F \in \mathcal{F}_h$, recalling that η_F is defined in Assumption 11, we let

$$\ell_F := k + 1 - \eta_F \leq k - 1. \quad (5.4)$$

Given a linear form $\mathcal{L}_F : \mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F) \rightarrow \mathbb{R}$, we consider the following problem: Find $(\boldsymbol{\sigma}, \boldsymbol{\lambda}) \in \mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F)$ such that

$$\mathcal{A}_F((\boldsymbol{\sigma}, \boldsymbol{\lambda}), (\boldsymbol{\tau}, \boldsymbol{\mu})) = \mathcal{L}_F(\boldsymbol{\tau}, \boldsymbol{\mu}) \quad \forall (\boldsymbol{\tau}, \boldsymbol{\mu}) \in \mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F), \quad (5.5)$$

with bilinear form $\mathcal{A}_F : [\mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F)]^2 \rightarrow \mathbb{R}$ such that

$$\mathcal{A}_F((\boldsymbol{v}, \boldsymbol{\nu}), (\boldsymbol{\tau}, \boldsymbol{\mu})) := h_F \sum_{E \in \mathcal{E}_F} \int_E (\boldsymbol{v} \cdot \boldsymbol{t}_E) (\boldsymbol{\tau} \cdot \boldsymbol{t}_E) + h_F^2 \int_F \operatorname{rot}_F \boldsymbol{v} \operatorname{rot}_F \boldsymbol{\tau} + \int_F \boldsymbol{v} \cdot \boldsymbol{\mu} - \int_F \boldsymbol{\tau} \cdot \boldsymbol{\nu}. \quad (5.6)$$

Proposition 15 (Well-posedness of the serendipity problem on faces). *The serendipity problem (5.5) admits a unique solution which satisfies*

$$\|(\boldsymbol{\sigma}, \boldsymbol{\lambda})\|_F := \|\boldsymbol{\sigma}\|_F + \|\boldsymbol{\lambda}\|_F \lesssim \|\mathcal{L}_F\|_F \quad (5.7)$$

where $\|\mathcal{L}_F\|_F$ is the norm of the linear form \mathcal{L}_F induced by the L^2 -norm on $\mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F)$.

Proof. The estimate (5.7) classically follows from the following inf-sup condition on \mathcal{A}_F : For all $(\boldsymbol{v}, \boldsymbol{\nu}) \in \mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F)$,

$$\|(\boldsymbol{v}, \boldsymbol{\nu})\|_F \lesssim \sup_{(\boldsymbol{\tau}, \boldsymbol{\mu}) \in \mathcal{P}^k(F) \times \mathcal{R}^{c, \ell_F+1}(F) \setminus \{(\mathbf{0}, \mathbf{0})\}} \frac{\mathcal{A}_F((\boldsymbol{v}, \boldsymbol{\nu}), (\boldsymbol{\tau}, \boldsymbol{\mu}))}{\|(\boldsymbol{\tau}, \boldsymbol{\mu})\|_F} =: \$. \quad (5.8)$$

Let us prove this condition. Taking $(\boldsymbol{\tau}, \boldsymbol{\mu}) = (\boldsymbol{v}, \boldsymbol{\nu})$ in the definition (5.6) of \mathcal{A}_F , we obtain

$$h_F \sum_{E \in \mathcal{E}_F} \|\boldsymbol{v} \cdot \boldsymbol{t}_E\|_E^2 + h_F^2 \|\operatorname{rot}_F \boldsymbol{v}\|_F^2 = \mathcal{A}_F((\boldsymbol{v}, \boldsymbol{\nu}), (\boldsymbol{v}, \boldsymbol{\nu})) \leq \$ \|(\boldsymbol{v}, \boldsymbol{\nu})\|_F. \quad (5.9)$$

We next notice that, for all $q \in \mathcal{P}^{0, k-1}(F)$,

$$\int_F \operatorname{rot}_F \boldsymbol{v} q = \int_F \boldsymbol{\pi}_{\mathcal{R}, F}^{k-2} \boldsymbol{v} \cdot \operatorname{rot}_F q - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E (\boldsymbol{v} \cdot \boldsymbol{t}_E) q.$$

Taking q such that $\operatorname{rot}_F q = \boldsymbol{\pi}_{\mathcal{R}, F}^{k-2} \boldsymbol{v}$ (which is possible since $\operatorname{rot}_F : \mathcal{P}^{0, k-1}(F) \rightarrow \mathcal{R}^{k-2}(F)$ is an isomorphism) and using Cauchy–Schwarz, discrete inverse, and trace inequalities along with $\|q\|_F \lesssim h_F \|\operatorname{rot}_F q\|_F = h_F \|\boldsymbol{\pi}_{\mathcal{R}, F}^{k-2} \boldsymbol{v}\|_F$ this gives, after simplifying and raising to the square,

$$\|\boldsymbol{\pi}_{\mathcal{R}, F}^{k-2} \boldsymbol{v}\|_F^2 \lesssim h_F \sum_{E \in \mathcal{E}_F} \|\boldsymbol{v} \cdot \boldsymbol{t}_E\|_E^2 + h_F^2 \|\operatorname{rot}_F \boldsymbol{v}\|_F^2 \lesssim \$ \|(\boldsymbol{v}, \boldsymbol{\nu})\|_F, \quad (5.10)$$

the conclusion being a consequence of (5.9). On the other hand, taking $(\boldsymbol{\tau}, \boldsymbol{\mu}) = (\mathbf{0}, \boldsymbol{\pi}_{\mathcal{R}, F}^{c, \ell_F+1} \boldsymbol{\nu})$ in the definition (5.6) of \mathcal{A}_F and recalling the definition (5.8) of $\$$, we obtain

$$\|\boldsymbol{\pi}_{\mathcal{R}, F}^{c, \ell_F+1} \boldsymbol{\nu}\|_F^2 = \mathcal{A}_F((\boldsymbol{v}, \boldsymbol{\nu}), (\mathbf{0}, \boldsymbol{\pi}_{\mathcal{R}, F}^{c, \ell_F+1} \boldsymbol{\nu})) \leq \$ \|\boldsymbol{\pi}_{\mathcal{R}, F}^{c, \ell_F+1} \boldsymbol{\nu}\|_F \leq \$ \|\boldsymbol{\nu}\|_F \leq \$ \|(\boldsymbol{v}, \boldsymbol{\nu})\|_F, \quad (5.11)$$

where the second inequality follows from the L^2 -boundedness of $\pi_{\mathcal{R},F}^{c,\ell_F+1}$. Summing (5.9), (5.10) and (5.11) and recalling (5.3) along with (5.4), we obtain

$$\|\mathbf{v}\|_F^2 \lesssim \mathcal{S}\|(\mathbf{v}, \boldsymbol{\nu})\|_F. \quad (5.12)$$

To estimate the L^2 -norm of $\boldsymbol{\nu}$, we notice that $\boldsymbol{\nu} \in \mathcal{P}^k(F)$ owing to (5.4), and we write

$$\begin{aligned} \|\boldsymbol{\nu}\|_F^2 &= \mathcal{A}_F((\mathbf{v}, \boldsymbol{\nu}), (-\boldsymbol{\nu}, \mathbf{0})) + h_F \sum_{E \in \mathcal{E}_F} \int_E (\mathbf{v} \cdot \mathbf{t}_E) (\boldsymbol{\nu} \cdot \mathbf{t}_E) + h_F^2 \int_F \operatorname{rot}_F \mathbf{v} \operatorname{rot}_F \boldsymbol{\nu} \\ &\lesssim \mathcal{S}\|\mathbf{v}\|_F + h_F^{\frac{1}{2}} \left(\sum_{E \in \mathcal{E}_F} \|\mathbf{v} \cdot \mathbf{t}_E\|_E^2 \right)^{\frac{1}{2}} \|\boldsymbol{\nu}\|_F + h_F \|\operatorname{rot}_F \mathbf{v}\|_F \|\boldsymbol{\nu}\|_F, \end{aligned}$$

where we have used Cauchy–Schwarz, discrete trace, and inverse inequalities to pass to the second line. Combining this estimate with (5.9), simplifying, and raising to the square, we conclude that

$$\|\boldsymbol{\nu}\|_F^2 \lesssim \mathcal{S}^2 + \mathcal{S}\|(\mathbf{v}, \boldsymbol{\nu})\|_F. \quad (5.13)$$

Summing (5.12) and (5.13), using Young’s inequality and taking the square root gives (5.8). \square

5.3.2 Serendipity spaces and operators

The serendipity gradient and curl spaces on a face $F \in \mathcal{F}_h$ are respectively defined as

$$\begin{aligned} \underline{\hat{\mathbf{X}}}_{\text{grad},F}^k &:= \left\{ \underline{\hat{q}}_F = (\hat{q}_F, \hat{q}_{\mathcal{E}_F}) : \hat{q}_F \in \mathcal{P}^{\ell_F}(F) \text{ and } \hat{q}_{\mathcal{E}_F} \in \mathcal{P}_c^{k+1}(\mathcal{E}_F) \right\}, \\ \underline{\hat{\mathbf{X}}}_{\text{curl},F}^k &:= \left\{ \underline{\hat{\mathbf{v}}}_F = (\hat{\mathbf{v}}_{\mathcal{R},F}, \hat{\mathbf{v}}_{\mathcal{R},F}^c, (\hat{\mathbf{v}}_E)_{E \in \mathcal{E}_F}) : \right. \\ &\quad \left. \hat{\mathbf{v}}_{\mathcal{R},F} \in \mathcal{R}^{k-1}(F), \hat{\mathbf{v}}_{\mathcal{R},F}^c \in \mathcal{R}^{c,\ell_F+1}(F), \text{ and } \hat{\mathbf{v}}_E \in \mathcal{P}^k(E) \text{ for all } E \in \mathcal{E}_F \right\}. \end{aligned}$$

We note that since these serendipity spaces are subspaces of $\underline{\mathbf{X}}_{\text{grad},F}^k$ and $\underline{\mathbf{X}}_{\text{curl},F}^k$, the components L^2 -norms defined by (4.2) can be applied to their elements.

The *gradient serendipity operator on faces* $\mathbf{S}_{\text{grad},F}^k : \underline{\hat{\mathbf{X}}}_{\text{grad},F}^k \rightarrow \mathcal{P}^k(F)$, the role of which is to reconstruct a consistent gradient (see Proposition 17 below), is defined, for all $\underline{\hat{q}}_F \in \underline{\hat{\mathbf{X}}}_{\text{grad},F}^k$, as the component $\boldsymbol{\sigma}$ of the unique solution to problem (5.5) with right-hand side linear form $\mathcal{L}_F = \mathcal{L}_{\text{grad},F}$ given by

$$\mathcal{L}_{\text{grad},F}(\underline{\hat{q}}_F; \boldsymbol{\tau}, \boldsymbol{\mu}) = h_F \sum_{E \in \mathcal{E}_F} \int_E \hat{q}'_E (\boldsymbol{\tau} \cdot \mathbf{t}_E) - \int_F \hat{q}_F \operatorname{div}_F \boldsymbol{\mu} + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{q}_E (\boldsymbol{\mu} \cdot \mathbf{n}_{FE}). \quad (5.14)$$

Combining the estimate (5.7) with Cauchy–Schwarz and discrete trace and inverse inequalities, we infer

$$\|\mathbf{S}_{\text{grad},F}^k \underline{\hat{q}}_F\|_F \lesssim h_F^{-1} \|\underline{\hat{q}}_F\|_{\text{grad},F} \quad \forall \underline{\hat{q}}_F \in \underline{\hat{\mathbf{X}}}_{\text{grad},F}^k. \quad (5.15)$$

The *curl serendipity operator on faces* $\mathbf{S}_{\text{curl},F}^k : \underline{\hat{\mathbf{X}}}_{\text{curl},F}^k \rightarrow \mathcal{P}^k(F)$, which reconstructs a consistent vector potential (as shown by Proposition 17 below), is defined for all $\underline{\hat{\mathbf{v}}}_F \in \underline{\hat{\mathbf{X}}}_{\text{curl},F}^k$ as the component $\boldsymbol{\sigma}$ of the unique solution to problem (5.5) with right-hand side linear form $\mathcal{L}_F = \mathcal{L}_{\text{curl},F}$ given by

$$\begin{aligned} \mathcal{L}_{\text{curl},F}(\underline{\hat{\mathbf{v}}}_F; \boldsymbol{\tau}, \boldsymbol{\mu}) &= h_F \sum_{E \in \mathcal{E}_F} \int_E \hat{\mathbf{v}}_E (\boldsymbol{\tau} \cdot \mathbf{t}_E) \\ &\quad + h_F^2 \left(\int_F \hat{\mathbf{v}}_{\mathcal{R},F} \cdot \operatorname{rot}_F \operatorname{rot}_F \boldsymbol{\tau} - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{\mathbf{v}}_E \operatorname{rot}_F \boldsymbol{\tau} \right) + \int_F \hat{\mathbf{v}}_{\mathcal{R},F}^c \cdot \boldsymbol{\mu}. \end{aligned} \quad (5.16)$$

The estimate (5.7) along with Cauchy–Schwarz and discrete trace and inverse inequalities yields

$$\|\mathbf{S}_{\text{curl},F}^k \underline{\hat{\mathbf{v}}}_F\|_F \lesssim \|\underline{\hat{\mathbf{v}}}_F\|_{\text{curl},F} \quad \forall \underline{\hat{\mathbf{v}}}_F \in \underline{\hat{\mathbf{X}}}_{\text{curl},F}^k. \quad (5.17)$$

5.3.3 Extensions and reductions

The *extensions on faces* $\underline{E}_{\text{grad},F} : \hat{\underline{X}}_{\text{grad},F}^k \rightarrow \underline{X}_{\text{grad},F}^k$ and $\underline{E}_{\text{curl},F} : \hat{\underline{X}}_{\text{curl},F}^k \rightarrow \underline{X}_{\text{curl},F}^k$ are such that

$$\underline{E}_{\text{grad},F} \hat{q}_F = (E_{\mathcal{P},F}^{k-1} \hat{q}_F, \hat{q}_{\mathcal{E}_F}) \quad \forall \hat{q}_F \in \hat{\underline{X}}_{\text{grad},F}^k, \quad (5.18)$$

$$\underline{E}_{\text{curl},F} \hat{v}_F = (\hat{v}_{\mathcal{R},F}, \pi_{\mathcal{R},F}^{c,k} \mathbf{S}_{\text{curl},F}^k \hat{v}_F, (\hat{v}_E)_{E \in \mathcal{E}_F}) \quad \forall \hat{v}_F \in \hat{\underline{X}}_{\text{curl},F}^k, \quad (5.19)$$

with $E_{\mathcal{P},F}^{k-1} : \hat{\underline{X}}_{\text{grad},F}^k \rightarrow \mathcal{P}^{k-1}(F)$ such that, for all $w_F \in \mathcal{R}^{c,k}(F)$,

$$\int_F E_{\mathcal{P},F}^{k-1} \hat{q}_F \operatorname{div}_F w_F = - \int_F \mathbf{S}_{\text{grad},F}^k \hat{q}_F \cdot w_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{q}_E (w_F \cdot \mathbf{n}_{FE}). \quad (5.20)$$

Using discrete trace inequalities, (5.15), (5.17), and the isomorphism property of $\operatorname{div}_F : \mathcal{R}^{c,k}(F) \rightarrow \mathcal{P}^{k-1}(F)$ stated in [14, Lemma 9], we get the following continuity properties:

$$\| \underline{E}_{\text{grad},F} \hat{q}_F \|_{\text{grad},F} \lesssim \| \hat{q}_F \|_{\text{grad},F} \quad \forall \hat{q}_F \in \hat{\underline{X}}_{\text{grad},F}^k, \quad (5.21)$$

$$\| \underline{E}_{\text{curl},F} \hat{v}_F \|_{\text{curl},F} \lesssim \| \hat{v}_F \|_{\text{curl},F} \quad \forall \hat{v}_F \in \hat{\underline{X}}_{\text{curl},F}^k. \quad (5.22)$$

The *reductions on faces*, which also define the interpolators $\hat{\underline{I}}_{\text{grad},F}^k$ on $\hat{\underline{X}}_{\text{grad},F}^k$ and $\hat{\underline{I}}_{\text{curl},F}^k$ on $\hat{\underline{X}}_{\text{curl},F}^k$ through (2.4), are $\hat{\underline{R}}_{\text{grad},F} : \underline{X}_{\text{grad},F}^k \rightarrow \hat{\underline{X}}_{\text{grad},F}^k$ and $\hat{\underline{R}}_{\text{curl},F} : \underline{X}_{\text{curl},F}^k \rightarrow \hat{\underline{X}}_{\text{curl},F}^k$ such that

$$\hat{\underline{R}}_{\text{grad},F} q_F = (\pi_{\mathcal{P},F}^{\ell_F} q_F, q_{\mathcal{E}_F}) \quad \forall q_F \in \underline{X}_{\text{grad},F}^k, \quad (5.23)$$

$$\hat{\underline{R}}_{\text{curl},F} v_F = (v_{\mathcal{R},F}, \pi_{\mathcal{R},F}^{c,\ell_F+1} v_{\mathcal{R},F}^c, (v_E)_{E \in \mathcal{E}_F}) \quad \forall v_F \in \underline{X}_{\text{curl},F}^k. \quad (5.24)$$

5.4 Serendipity, extension, and reduction operators on elements

5.4.1 Serendipity problem

For a fixed element $T \in \mathcal{T}_h$, recalling that η_T is given by Assumption 11, we let

$$\ell_T := k + 1 - \eta_T \leq k - 1 \quad (5.25)$$

and, given a linear form $\mathcal{L}_T : \mathcal{P}^k(T) \times \mathcal{R}^{c,\ell_T+1}(T) \rightarrow \mathbb{R}$, consider the following problem: Find $(\sigma, \lambda) \in \mathcal{P}^k(T) \times \mathcal{R}^{c,\ell_T+1}(T)$ such that

$$\mathcal{A}_T((\sigma, \lambda), (\tau, \mu)) = \mathcal{L}_T(\tau, \mu) \quad \forall (\tau, \mu) \in \mathcal{P}^k(T) \times \mathcal{R}^{c,\ell_T+1}(T), \quad (5.26)$$

with bilinear form $\mathcal{A}_T : [\mathcal{P}^k(T) \times \mathcal{R}^{c,\ell_T+1}(T)]^2 \rightarrow \mathbb{R}$ such that

$$\mathcal{A}_T((v, \nu), (\tau, \mu)) := h_T \sum_{F \in \mathcal{F}_T} \int_F v_{t,F} \cdot \tau_{t,F} + h_T^2 \int_T \mathbf{curl} v \cdot \mathbf{curl} \tau + \int_T v \cdot \mu - \int_T \tau \cdot \nu.$$

We remind the reader that, for any $v : T \rightarrow \mathbb{R}^3$ smooth enough and any $F \in \mathcal{F}_T$, $v_{t,F} := \mathbf{n}_F \times (v|_F \times \mathbf{n}_F)$ denotes the tangential component of v on F . Proceeding as in the proof of Proposition 15, we can prove the following result.

Proposition 16 (Well-posedness of the serendipity problem on elements). *The serendipity problem (5.26) admits a unique solution which satisfies*

$$\| \sigma \|_T + \| \lambda \|_T \lesssim \| \mathcal{L}_T \|_T \quad (5.27)$$

where $\| \mathcal{L}_T \|_T$ is the norm of the linear form \mathcal{L}_T induced by the L^2 -norm on $\mathcal{P}^k(T) \times \mathcal{R}^{c,\ell_T+1}(T)$.

5.4.2 Serendipity spaces and operators

The serendipity spaces on an element $T \in \mathcal{T}_h$ are defined as

$$\underline{\hat{X}}_{\text{grad},T}^k := \left\{ \underline{\hat{q}}_T = (\hat{q}_T, (\hat{q}_F)_{F \in \mathcal{F}_T}, \hat{q}_{\mathcal{E}_T}) : \hat{q}_T \in \mathcal{P}^{\ell_T}(T), \hat{q}_F \in \mathcal{P}^{\ell_F}(F) \text{ for all } F \in \mathcal{F}_T, \right. \\ \left. \text{and } \hat{q}_{\mathcal{E}_T} \in \mathcal{P}_c^{k+1}(\mathcal{E}_T) \right\},$$

$$\underline{\hat{X}}_{\text{curl},T}^k := \left\{ \underline{\hat{v}}_T = (\hat{v}_{\mathcal{R},T}, \hat{v}_{\mathcal{R},T}^c, (\hat{v}_{\mathcal{R},F}, \hat{v}_{\mathcal{R},F}^c)_{F \in \mathcal{F}_T}, (\hat{v}_E)_{E \in \mathcal{E}_T}) : \right. \\ \hat{v}_{\mathcal{R},T} \in \mathcal{R}^{k-1}(T) \text{ and } \hat{v}_{\mathcal{R},T}^c \in \mathcal{R}^{c,\ell_T+1}(T), \\ \hat{v}_{\mathcal{R},F} \in \mathcal{R}^{k-1}(F) \text{ and } \hat{v}_{\mathcal{R},F}^c \in \mathcal{R}^{c,\ell_F+1}(F) \text{ for all } F \in \mathcal{F}_T, \\ \left. \text{and } \hat{v}_E \in \mathcal{P}^k(E) \text{ for all } E \in \mathcal{E}_T \right\}.$$

The component norms defined by (4.2) naturally apply to these spaces.

The *gradient serendipity operator on elements* $\mathbf{S}_{\text{grad},T}^k : \underline{\hat{X}}_{\text{grad},T}^k \rightarrow \mathcal{P}^k(T)$ is defined, for all $\underline{\hat{q}}_T \in \underline{\hat{X}}_{\text{grad},T}^k$, as the component σ of the unique solution to problem (5.26) with $\mathcal{L}_T = \mathcal{L}_{\text{grad},T}$, where

$$\mathcal{L}_{\text{grad},T}(\underline{\hat{q}}_T; \tau, \mu) = h_T \sum_{F \in \mathcal{F}_T} \int_F \mathbf{G}_F^k \underline{E}_{\text{grad},F} \underline{\hat{q}}_F \cdot \tau_{\iota,F} \\ - \int_T \hat{q}_T \operatorname{div} \mu + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{E}_{\text{grad},F} \underline{\hat{q}}_F (\mu \cdot \mathbf{n}_F). \quad (5.28)$$

Combining the a priori estimate (5.27) with Cauchy–Schwarz and discrete trace and inverse inequalities, observing that $\|\mathbf{G}_F^k \underline{E}_{\text{grad},F} \underline{\hat{q}}_F\|_F \lesssim h_F^{-1} \|\underline{\hat{q}}_F\|_{\text{grad},F}$ by (4.5) for $(\mathbf{P}, \underline{q}_{\mathbf{P}}) = (F, \underline{E}_{\text{grad},F} \underline{\hat{q}}_F)$ followed by (5.21), and that $\|\gamma_F^{k+1} \underline{E}_{\text{grad},F} \underline{\hat{q}}_F\|_F \lesssim \|\underline{\hat{q}}_F\|_{\text{grad},F}$ (consequence of [14, Proposition 6] followed by (5.21)),

$$\|\mathbf{S}_{\text{grad},T}^k \underline{\hat{q}}_T\|_T \lesssim h_T^{-1} \|\underline{\hat{q}}_T\|_{\text{grad},T} \quad \forall \underline{\hat{q}}_T \in \underline{\hat{X}}_{\text{grad},T}^k. \quad (5.29)$$

The *curl serendipity operator on elements* $\mathbf{S}_{\text{curl},T}^k : \underline{\hat{X}}_{\text{curl},T}^k \rightarrow \mathcal{P}^k(T)$ is defined, for all $\underline{\hat{v}}_T \in \underline{\hat{X}}_{\text{curl},T}^k$, as the component σ of the unique solution to problem (5.26) with $\mathcal{L}_T := \mathcal{L}_{\text{curl},T}$ defined by

$$\mathcal{L}_{\text{curl},T}(\underline{\hat{v}}_T; \tau, \mu) = h_T \sum_{F \in \mathcal{F}_T} \int_F \gamma_{\iota,F}^k \underline{E}_{\text{curl},F} \underline{\hat{v}}_F \cdot \tau_{\iota,F} \\ + h_T^2 \left(\int_T \hat{v}_{\mathcal{R},T} \cdot \operatorname{curl} \operatorname{curl} \tau + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_{\iota,F}^k \underline{E}_{\text{curl},F} \underline{\hat{v}}_F \cdot (\operatorname{curl} \tau \times \mathbf{n}_F) \right) + \int_T \hat{v}_{\mathcal{R},T}^c \cdot \mu. \quad (5.30)$$

Using the a priori estimate (5.27), Cauchy–Schwarz and discrete trace and inverse inequalities, as well as estimates of $\gamma_{\iota,F}^k \underline{E}_{\text{curl},F} \underline{\hat{v}}_F$ following from [14, Proposition 6] and (5.22), we have

$$\|\mathbf{S}_{\text{curl},T}^k \underline{\hat{v}}_T\|_T \lesssim \|\underline{\hat{v}}_T\|_{\text{curl},T} \quad \forall \underline{\hat{v}}_T \in \underline{\hat{X}}_{\text{curl},T}^k. \quad (5.31)$$

5.4.3 Extensions and reductions

The *extensions on elements* are $\underline{E}_{\text{grad},T} : \underline{\hat{X}}_{\text{grad},T}^k \rightarrow \underline{X}_{\text{grad},T}^k$ and $\underline{E}_{\text{curl},T} : \underline{\hat{X}}_{\text{curl},T}^k \rightarrow \underline{X}_{\text{curl},T}^k$ such that

$$\underline{E}_{\text{grad},T} \underline{\hat{q}}_T = (E_{\mathcal{P},T}^{k-1} \hat{q}_T, (E_{\mathcal{P},F}^{k-1} \hat{q}_F)_{F \in \mathcal{F}_T}, \hat{q}_{\mathcal{E}_T}) \quad \forall \underline{\hat{q}}_T \in \underline{\hat{X}}_{\text{grad},T}^k, \quad (5.32)$$

$$\underline{E}_{\text{curl},T} \underline{\hat{v}}_T = (\hat{v}_{\mathcal{R},T}, \pi_{\mathcal{R},T}^{c,k} \mathbf{S}_{\text{curl},T}^k \underline{\hat{v}}_T, (\hat{v}_{\mathcal{R},F}, \pi_{\mathcal{R},F}^{c,k} \mathbf{S}_{\text{curl},F}^k \underline{\hat{v}}_F)_{F \in \mathcal{F}_T}, (\hat{v}_E)_{E \in \mathcal{E}_T}) \quad \forall \underline{\hat{v}}_T \in \underline{\hat{X}}_{\text{curl},T}^k, \quad (5.33)$$

with $E_{\mathcal{P},F}^{k-1}$ defined by (5.20) and $E_{\mathcal{P},T}^{k-1} : \hat{X}_{\text{grad},T}^k \rightarrow \mathcal{P}^{k-1}(T)$ such that, for all $\mathbf{w}_T \in \mathcal{R}^{c,k}(T)$,

$$\int_T E_{\mathcal{P},T}^{k-1} \hat{q}_T \operatorname{div} \mathbf{w}_T = - \int_T \mathbf{S}_{\text{grad},T}^k \hat{q}_T \cdot \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{E}_{\text{grad},F} \hat{q}_F (\mathbf{w}_T \cdot \mathbf{n}_{TE}).$$

Proceeding in a similar way as for the face extensions, (5.29) and (5.31) yield

$$\begin{aligned} \|\underline{E}_{\text{grad},T} \hat{q}_T\|_{\text{grad},T} &\lesssim \|\hat{q}_T\|_{\text{grad},T} & \forall \hat{q}_T \in \hat{X}_{\text{grad},T}^k, \\ \|\underline{E}_{\text{curl},T} \hat{\mathbf{v}}_T\|_{\text{curl},T} &\lesssim \|\hat{\mathbf{v}}_T\|_{\text{curl},T} & \forall \hat{\mathbf{v}}_T \in \hat{X}_{\text{curl},T}^k. \end{aligned} \quad (5.34)$$

The reductions on elements are $\hat{R}_{\text{grad},T} : X_{\text{grad},T}^k \rightarrow \hat{X}_{\text{grad},T}^k$ and $\hat{R}_{\text{curl},T} : X_{\text{curl},T}^k \rightarrow \hat{X}_{\text{curl},T}^k$ such that

$$\hat{R}_{\text{grad},T} q_T = (\hat{R}_{\mathcal{P},T}^{\ell_T} q_T, (\pi_{\mathcal{P},F}^{\ell_F} q_F)_{F \in \mathcal{F}_T}, q_{\mathcal{E}_T}) \quad \forall q_T \in X_{\text{grad},T}^k, \quad (5.35)$$

$$\hat{R}_{\text{curl},T} \mathbf{v}_T = (\hat{R}_{\mathcal{R},T}^{k-1} \mathbf{v}_T, \pi_{\mathcal{R},T}^{c,\ell_T+1} \mathbf{v}_{\mathcal{R},T}^c, (\mathbf{v}_{\mathcal{R},F}, \pi_{\mathcal{R},F}^{c,\ell_F+1} \mathbf{v}_{\mathcal{R},F}^c)_{F \in \mathcal{F}_T}, (\mathbf{v}_E)_{E \in \mathcal{E}_T}) \quad \forall \mathbf{v}_T \in X_{\text{curl},T}^k, \quad (5.36)$$

where $\hat{R}_{\mathcal{P},T}^{\ell_T} q_T \in \mathcal{P}^{\ell_T}(T)$ is such that, for all $\mathbf{w}_T \in \mathcal{R}^{c,\ell_T+1}(T)$,

$$\int_T \hat{R}_{\mathcal{P},T}^{\ell_T} q_T \operatorname{div} \mathbf{w}_T = - \int_T \mathbf{C}_T^k q_T \cdot \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{E}_{\text{grad},F} \hat{R}_{\text{grad},F} q_F (\mathbf{w}_T \cdot \mathbf{n}_F) \quad (5.37)$$

while $\hat{R}_{\mathcal{R},T}^{k-1} \mathbf{v}_T \in \mathcal{R}^{k-1}(T)$ is such that, for all $\mathbf{w}_T \in \mathcal{G}^{c,k}(T)$,

$$\int_T \hat{R}_{\mathcal{R},T}^{k-1} \mathbf{v}_T \cdot \operatorname{curl} \mathbf{w}_T = \int_T \mathbf{C}_T^k \mathbf{v}_T \cdot \mathbf{w}_T - \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_{t,F}^k \underline{E}_{\text{curl},F} \hat{R}_{\text{curl},F} \mathbf{v}_F \cdot (\mathbf{w}_T \times \mathbf{n}_F). \quad (5.38)$$

6 Properties of the SDDR complex

6.1 Preliminary results

Proposition 17 (Polynomial consistency of the serendipity operators and extensions). *The serendipity operators and extensions enjoy the following polynomial consistency properties: For all $\mathbb{P} \in \mathcal{T}_h \cup \mathcal{F}_h$,*

$$\mathbf{S}_{\text{grad},\mathbb{P}}^k \hat{I}_{\text{grad},\mathbb{P}}^k q = \mathbf{grad}_{\mathbb{P}} q \quad \forall q \in \mathcal{P}^{k+1}(\mathbb{P}), \quad (6.1)$$

$$\underline{E}_{\text{grad},\mathbb{P}} \hat{I}_{\text{grad},\mathbb{P}}^k q = \underline{I}_{\text{grad},\mathbb{P}}^k q \quad \forall q \in \mathcal{P}^{k+1}(\mathbb{P}), \quad (6.2)$$

$$\mathbf{S}_{\text{curl},\mathbb{P}}^k \hat{I}_{\text{curl},\mathbb{P}}^k \mathbf{v} = \mathbf{v} \quad \forall \mathbf{v} \in \mathcal{P}^k(\mathbb{P}), \quad (6.3)$$

$$\underline{E}_{\text{curl},\mathbb{P}} \hat{I}_{\text{curl},\mathbb{P}}^k \mathbf{v} = \underline{I}_{\text{curl},\mathbb{P}}^k \mathbf{v} \quad \forall \mathbf{v} \in \mathcal{P}^k(\mathbb{P}). \quad (6.4)$$

Proof. Let us first consider the case $\mathbb{P} = F \in \mathcal{F}_h$. Let $q \in \mathcal{P}^{k+1}(F)$. By uniqueness of the solution to (5.5), (6.1) follows from proving that $(\mathbf{grad}_F q, \mathbf{0})$ solves this problem with $\mathcal{L}_F = \mathcal{L}_{\text{grad},F}$ defined by (5.14) with $\hat{q}_F = \hat{I}_{\text{grad},F}^k q$. Recalling the definition (5.6) of \mathcal{A}_F , it holds, for all $(\boldsymbol{\tau}, \boldsymbol{\mu}) \in \mathcal{P}^k(F) \times \mathcal{R}^{c,\ell_F+1}(F)$,

$$\begin{aligned} \mathcal{A}_F((\mathbf{grad}_F q, \mathbf{0}), (\boldsymbol{\tau}, \boldsymbol{\mu})) &= h_F \sum_{E \in \mathcal{E}_F} \int_E (\mathbf{grad}_F q \cdot \mathbf{t}_E) (\boldsymbol{\tau} \cdot \mathbf{t}_E) + \int_F \mathbf{grad}_F q \cdot \boldsymbol{\mu} \\ &= h_F \sum_{E \in \mathcal{E}_F} \int_E q'_E (\boldsymbol{\tau} \cdot \mathbf{t}_E) - \int_F \pi_{\mathcal{P},F}^{\ell_F} q \operatorname{div}_F \boldsymbol{\mu} + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \pi_{\mathcal{P},E}^{k-1} q (\boldsymbol{\mu} \cdot \mathbf{n}_{FE}) \\ &= \mathcal{L}_{\text{grad},F}(\hat{I}_{\text{grad},F}^k q; \boldsymbol{\tau}, \boldsymbol{\mu}), \end{aligned}$$

where we have used $\text{rot}_F \mathbf{grad}_F = 0$ in the first line, an integration by parts along with the fact that $\text{div}_F \boldsymbol{\mu} \in \mathcal{P}^{\ell_F}(F)$ and, for all $E \in \mathcal{E}_F$, $\boldsymbol{\mu} \cdot \mathbf{n}_{FE} \in \mathcal{P}^{\ell_F}(E) \subset \mathcal{P}^{k-1}(E)$ (see [14, Proposition 8]) to insert $\pi_{\mathcal{P},F}^{\ell_F}$ and $\pi_{\mathcal{P},E}^{k-1}$ in the second line, and the definition of $\hat{\mathbf{I}}_{\text{grad},F}^k$ (based on (2.4) with full interpolator and reduction respectively given by (4.9) and (5.23)) together with (5.14) to conclude. This proves (6.1) for $P = F$. From this result, using an integration by parts in (5.20) together with the fact that $\text{div}_F : \mathcal{R}^{c,k}(F) \rightarrow \mathcal{P}^{k-1}(F)$ is an isomorphism, we infer that $E_{\mathcal{P},F}^{k-1} \hat{\mathbf{I}}_{\text{grad},F}^k q = \pi_{\mathcal{P},F}^{k-1} q$, which gives (6.2).

We proceed similarly to prove (6.3) for $P = F$. Specifically, let $\mathbf{v} \in \mathcal{P}^k(F)$. For all $(\boldsymbol{\tau}, \boldsymbol{\mu}) \in \mathcal{P}^k(F) \times \mathcal{R}^{c,\ell_F+1}(F)$, it holds

$$\begin{aligned} \mathcal{A}_F((\mathbf{v}, \mathbf{0}), (\boldsymbol{\tau}, \boldsymbol{\mu})) &= h_F \sum_{E \in \mathcal{E}_F} \int_E (\mathbf{v} \cdot \mathbf{t}_E) (\boldsymbol{\tau} \cdot \mathbf{t}_E) + h_F^2 \int_F \text{rot}_F \mathbf{v} \text{rot}_F \boldsymbol{\tau} + \int_F \mathbf{v} \cdot \boldsymbol{\mu} \\ &= h_F \sum_{E \in \mathcal{E}_F} \int_E \pi_{\mathcal{P},E}^k (\mathbf{v} \cdot \mathbf{t}_E) (\boldsymbol{\tau} \cdot \mathbf{t}_E) \\ &\quad + h_F^2 \left(\int_F \pi_{\mathcal{R},F}^{k-2} \mathbf{v} \cdot \text{rot}_F \text{rot}_F \boldsymbol{\tau} - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \pi_{\mathcal{P},E}^k (\mathbf{v} \cdot \mathbf{t}_E) \text{rot}_F \boldsymbol{\tau} \right) + \int_F \pi_{\mathcal{R},F}^{c,\ell_F+1} \mathbf{v} \cdot \boldsymbol{\mu} \\ &= \mathcal{L}_{\text{curl},F}(\hat{\mathbf{I}}_{\text{curl},F}^k \mathbf{v}; (\boldsymbol{\tau}, \boldsymbol{\mu})), \end{aligned}$$

where we have used an integration by parts along with the definitions of the L^2 -orthogonal projectors to pass to the second line, and (5.16) together with the definition of $\hat{\mathbf{I}}_{\text{curl},F}^k$ (obtained, according to (2.4), composing (5.24) and the L^2 -projectors on the components of $\underline{\mathbf{X}}_{\text{curl},F}^k$) to conclude. This proves that $(\mathbf{v}, \mathbf{0})$ solves (5.5) with $\mathcal{L}_F = \mathcal{L}_{\text{curl},F}$ given by (5.16) with $\hat{\mathbf{v}}_F = \hat{\mathbf{I}}_{\text{curl},F}^k \mathbf{v}$. This establishes (6.3), from which (6.4) immediately follows.

We now briefly discuss the case $P = T \in \mathcal{T}_h$. Let $q \in \mathcal{P}^{k+1}(T)$. Using $\hat{\mathbf{R}}_{\text{grad},Q} \mathbf{I}_{\text{grad},Q}^k = \hat{\mathbf{I}}_{\text{grad},Q}^k$ for $Q \in \mathcal{T}_h \cup \mathcal{F}_h$ (by definition (2.4)), (6.2) for $P = F$, and the polynomial consistencies of \mathbf{G}_T^k and γ_F^{k+1} (see [14, Lemma 3]), the definition (5.37) shows that the element component of $\hat{\mathbf{I}}_{\text{grad},T}^k q$ is $\hat{\mathbf{R}}_{\mathcal{P},T}^{\ell_T} \mathbf{I}_{\text{grad},T}^k q = \pi_{\mathcal{P},T}^{\ell_T} q$. We can then proceed as above, using the polynomial consistency of \mathbf{G}_F^k and γ_F^{k+1} together with (6.2) for $P = F$ to see that (6.1) and (6.2) hold for $P = T$.

The proof of (6.3) and (6.4) for $P = T$ is similar, noticing that the polynomial consistencies of $\boldsymbol{\gamma}_{T,F}^k$ and \mathbf{C}_T^k (see [14, Eqs. (3.25) and (3.29)]) and (6.4) for $P = F$ yield $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \mathbf{I}_{\text{curl},T}^k \mathbf{v} = \pi_{\mathcal{R},T}^{k-1} \mathbf{v}$. \square

Lemma 18 (Projections of extension, serendipity and gradient operators). *For all $P \in \mathcal{T}_h \cup \mathcal{F}_h$, it holds:*

$$\pi_{\mathcal{P},P}^{\ell_P} E_{\mathcal{P},P}^{k-1} \hat{q}_P = \hat{q}_P \quad \forall \hat{q}_P \in \hat{\mathbf{X}}_{\text{grad},P}^k, \quad (6.5)$$

$$\pi_{\mathcal{R},P}^{c,k} \mathbf{G}_P^k E_{\text{grad},P}^k \hat{q}_P = \pi_{\mathcal{R},P}^{c,k} \mathbf{S}_{\text{grad},P}^k \hat{q}_P \quad \forall \hat{q}_P \in \hat{\mathbf{X}}_{\text{grad},P}^k. \quad (6.6)$$

$$\pi_{\mathcal{R},F}^{c,\ell_P+1} \mathbf{S}_{\text{curl},P}^k \hat{\mathbf{v}}_P = \hat{\mathbf{v}}_{\mathcal{R},P}^c \quad \forall \hat{\mathbf{v}}_P \in \hat{\mathbf{X}}_{\text{curl},P}^k. \quad (6.7)$$

Proof. We focus, for the sake of brevity, on the case $P = F \in \mathcal{F}_h$, the case $P = T \in \mathcal{T}_h$ being similar. Taking a generic $\mathbf{w}_F \in \mathcal{R}^{c,\ell_F+1}(F)$ and plugging $(\boldsymbol{\tau}, \boldsymbol{\mu}) = (\mathbf{0}, \mathbf{w}_F)$ into the variational problem defining $\mathbf{S}_{\text{grad},F}^k \hat{q}_F$ (i.e., (5.5) with $\mathcal{L}_F = \mathcal{L}_{\text{grad},F}$ given by (5.14)), we infer that

$$\int_F \mathbf{S}_{\text{grad},F}^k \hat{q}_F \cdot \mathbf{w}_F = - \int_F \hat{q}_F \text{div}_F \mathbf{w}_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{q}_E (\mathbf{w}_F \cdot \mathbf{n}_{FE}). \quad (6.8)$$

Writing the definition (5.20) of $E_{\mathcal{P},F}^{k-1}$ with this choice of \mathbf{w}_F (which is possible since $\mathcal{R}^{c,\ell_F+1}(F) \subset \mathcal{R}^{c,k}(F)$ by (5.4)) and subtracting (6.8) from the resulting expression yields

$$\int_F E_{\mathcal{P},F}^{k-1} \hat{\underline{q}}_F \operatorname{div}_F \mathbf{w}_F = \int_F \hat{q}_F \operatorname{div}_F \mathbf{w}_F,$$

which proves (6.5) since $\operatorname{div}_F : \mathcal{R}^{c,\ell_F+1}(F) \rightarrow \mathcal{P}^{\ell_F}(F)$ is an isomorphism. To establish (6.6), we take $\mathbf{w}_F \in \mathcal{R}^{c,k}(F)$ and write the definition (4.3) of $\mathbf{G}_F^k \underline{E}_{\operatorname{grad},F} \hat{\underline{q}}_F$ to get

$$\int_F \mathbf{G}_F^k \underline{E}_{\operatorname{grad},F} \hat{\underline{q}}_F \cdot \mathbf{w}_F = - \int_F E_{\mathcal{P},F}^{k-1} \hat{\underline{q}}_F \operatorname{div}_F \mathbf{w}_F + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{q}_E (\mathbf{w}_F \cdot \mathbf{n}_{FE}) = \int_F \mathbf{S}_{\operatorname{grad},F}^k \hat{\underline{q}}_F \cdot \mathbf{w}_F,$$

where the second equality follows from the definition (5.20) of $E_{\mathcal{P},F}^{k-1}$. Finally, to prove (6.7), it suffices to take test functions of the form $(\mathbf{0}, \boldsymbol{\mu})$, with $\boldsymbol{\mu}$ spanning $\mathcal{R}^{c,\ell_F+1}(F)$, in the problem defining $\mathbf{S}_{\operatorname{curl},F}^k \hat{\underline{p}}_F$ (i.e., (5.5) with right-hand side $\mathcal{L}_F = \mathcal{L}_{\operatorname{curl},F}$ given by (5.16)). \square

Lemma 19 (Equivalence of norms on $\hat{\underline{X}}_{\operatorname{grad},T}^k$ and $\hat{\underline{X}}_{\operatorname{curl},T}^k$). *For $\bullet \in \{\operatorname{grad}, \operatorname{curl}\}$, it holds $\|\cdot\|_{\bullet,s,T} \simeq \|\cdot\|_{\bullet,T}$ on $\hat{\underline{X}}_{\bullet,T}^k$ where, in accordance with (2.3), $\|\cdot\|_{\bullet,s,T} := \|\underline{E}_{\bullet,T} \cdot\|_{\bullet,T}$ with $\|\cdot\|_{\bullet,T}$ defined in Section 4.4.*

Proof. We only consider the case $\bullet = \operatorname{grad}$, the proof for $\bullet = \operatorname{curl}$ being similar. For all $\hat{\underline{q}}_T \in \hat{\underline{X}}_{\operatorname{grad},T}^k$, we have

$$\|\hat{\underline{q}}_T\|_{\operatorname{grad},s,T} = \|\underline{E}_{\operatorname{grad},T} \hat{\underline{q}}_T\|_{\operatorname{grad},T} \lesssim \|\underline{E}_{\operatorname{grad},T} \hat{\underline{q}}_T\|_{\operatorname{grad},T} \lesssim \|\hat{\underline{q}}_T\|_{\operatorname{grad},T},$$

where the first inequality comes from the equivalence of norms on $\underline{X}_{\operatorname{grad},T}^k$, see [14, Lemma 5], and the second inequality is (5.34). To prove the converse inequality, we use (6.5) to write

$$\begin{aligned} \|\hat{\underline{q}}_T\|_{\operatorname{grad},T}^2 &= \|\pi_{\mathcal{P},T}^{\ell_T} E_{\mathcal{P},T}^{k-1} \hat{\underline{q}}_T\|_T^2 + \sum_{F \in \mathcal{F}_T} h_F \|\pi_{\mathcal{P},F}^{\ell_F} E_{\mathcal{P},F}^{k-1} \hat{\underline{q}}_F\|_F^2 + \sum_{F \in \mathcal{F}_T} h_F \sum_{E \in \mathcal{E}_F} h_E \|q_E\|_E^2 \\ &\leq \|\underline{E}_{\operatorname{grad},T} \hat{\underline{q}}_T\|_{\operatorname{grad},T}^2, \end{aligned}$$

where the last bound follows from the L^2 -boundedness of the L^2 -projectors and the definition (5.32) of $\underline{E}_{\operatorname{grad},T} \hat{\underline{q}}_T$. We then invoke the equivalence of norms in $\underline{X}_{\operatorname{grad},T}^k$ (see [14, Lemma 5]) to get $\|\underline{E}_{\operatorname{grad},T} \hat{\underline{q}}_T\|_{\operatorname{grad},T}^2 \lesssim \|\underline{E}_{\operatorname{grad},T} \hat{\underline{q}}_T\|_{\operatorname{grad},T}^2 = \|\hat{\underline{q}}_T\|_{\operatorname{grad},s,T}^2$. \square

6.2 Commutation property for the serendipity operators

The property in the following lemma justifies the choice of serendipity operators made in Sections 5.3.2 and 5.4.2 and will play a crucial role in the proof of Lemma 23 below (cochain property for the extension map).

Lemma 20 (Commutation property for the serendipity operators). *For all $\mathbf{P} \in \mathcal{T}_h \cup \mathcal{F}_h$, it holds, recalling that $\hat{\underline{G}}_{\mathbf{P}}^k := \hat{\underline{R}}_{\operatorname{curl},\mathbf{P}} \mathbf{G}_{\mathbf{P}}^k \underline{E}_{\operatorname{grad},\mathbf{P}}$ by (2.2),*

$$\mathbf{S}_{\operatorname{curl},\mathbf{P}}^k \hat{\underline{G}}_{\mathbf{P}}^k \hat{\underline{q}}_{\mathbf{P}} = \mathbf{S}_{\operatorname{grad},\mathbf{P}}^k \hat{\underline{q}}_{\mathbf{P}} \quad \forall \hat{\underline{q}}_{\mathbf{P}} \in \hat{\underline{X}}_{\operatorname{grad},\mathbf{P}}^k, \quad (6.9)$$

which expresses the fact that the following diagram commutes:

$$\begin{array}{ccc} \hat{\underline{X}}_{\operatorname{grad},\mathbf{P}}^k & \xrightarrow{\mathbf{S}_{\operatorname{grad},\mathbf{P}}^k} & \mathcal{P}^k(\mathbf{P}) \\ & \searrow \hat{\underline{G}}_{\mathbf{P}}^k & \uparrow \mathbf{S}_{\operatorname{curl},\mathbf{P}}^k \\ & & \hat{\underline{X}}_{\operatorname{curl},\mathbf{P}}^k \end{array}$$

Proof. Let us consider $P = F$, and set, for the sake of brevity, $\hat{\underline{v}}_F := \hat{\mathbf{G}}_F^k \hat{\underline{q}}_F$. Then, $\hat{v}_E = \hat{q}'_E$ and

$$\hat{\underline{v}}_{\mathcal{R},F}^c = \pi_{\mathcal{R},F}^{c,\ell_F+1} \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{\underline{q}}_F = \pi_{\mathcal{R},F}^{c,\ell_F+1} \mathbf{S}_{\text{grad},F}^k \hat{\underline{q}}_F \quad (6.10)$$

by (6.6) for $P = F$ recalling (3.3) along with $\ell_F + 1 \leq k$ (cf. (5.4)). Moreover, for all $z_F \in \mathcal{P}^k(F)$,

$$\begin{aligned} \int_F \hat{\underline{v}}_{\mathcal{R},F} \cdot \mathbf{rot}_F z_F - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{v}_E z_F &= \int_F \pi_{\mathcal{R},F}^{k-1} \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{\underline{q}}_F \cdot \mathbf{rot}_F z_F - \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{q}'_E z_F \\ &= \int_F C_F^k \mathbf{G}_F^k \underline{E}_{\text{grad},F} z_F = 0, \end{aligned} \quad (6.11)$$

where, to pass to the second line, we have invoked the definition (4.6) of C_F^k together with the fact that the edge components of $\underline{E}_{\text{grad},F} \hat{\underline{q}}_F$ are $(\hat{q}'_E)_{E \in \mathcal{E}_F}$, and we have concluded thanks to the local complex property stated in [14, Proposition 2]. We next notice that, recalling (6.10) and (6.8), for all $\mu \in \mathcal{R}^{c,\ell_F+1}(F)$,

$$\int_F \hat{\underline{v}}_{\mathcal{R},F}^c \cdot \mu = \int_F \mathbf{S}_{\text{grad},F}^k \hat{\underline{q}}_F \cdot \mu = - \int_F \hat{q}_F \operatorname{div}_F \mu + \sum_{E \in \mathcal{E}_F} \omega_{FE} \int_E \hat{q}_E (\mu \cdot \mathbf{n}_{FE}). \quad (6.12)$$

Recalling that $v_E = \hat{q}'_E$ for all $E \in \mathcal{E}_h$, plugging (6.11) and (6.12) into the expression (5.16) of the linear form $\mathcal{L}_{\text{curl},F}(\hat{\underline{v}}_F; \cdot, \cdot)$, and recalling the expression (5.14) of the linear form $\mathcal{L}_{\text{grad},F}$, we conclude that $\mathcal{L}_{\text{curl},F}(\hat{\underline{v}}_F; \tau, \mu) = \mathcal{L}_{\text{grad},F}(\hat{\underline{q}}_F; \tau, \mu)$ for all $(\tau, \mu) \in \mathcal{P}^k(F) \times \mathcal{R}^{c,\ell_F+1}(F)$. Letting $\lambda_{\hat{\underline{v}}_F}, \lambda_{\hat{\underline{q}}_F} \in \mathcal{R}^{c,\ell_F+1}(F)$ be the second components in the serendipity problems (5.5) defining $\mathbf{S}_{\text{curl},F}^k \hat{\underline{v}}_F$ and $\mathbf{S}_{\text{grad},F}^k \hat{\underline{q}}_F$, respectively, this implies

$$\mathcal{A}_F((\mathbf{S}_{\text{curl},F}^k \hat{\underline{v}}_F - \mathbf{S}_{\text{grad},F}^k \hat{\underline{q}}_F, \lambda_{\hat{\underline{v}}_F} - \lambda_{\hat{\underline{q}}_F}), (\tau, \mu)) = 0 \quad \forall (\tau, \mu) \in \mathcal{P}^k \times \mathcal{R}^{c,\ell_F+1}(F),$$

showing that $\mathbf{S}_{\text{curl},F}^k \hat{\underline{v}}_F = \mathbf{S}_{\text{grad},F}^k \hat{\underline{q}}_F$. The proof in the case $P = T \in \mathcal{T}_h$ is similar. The details are left to the reader. \square

6.3 Homological and analytical properties for the gradient

Lemma 21 (Properties of the serendipity gradient space). *The serendipity construction for the gradient space satisfies both the homological properties of Assumption 1 and the analytical properties of Assumption 3, with continuity constants in (A1) and (A3) that do not depend on h .*

Proof. (i) *Proof of (CI).* Let $T \in \mathcal{T}_h$ and $\hat{\underline{q}}_T \in \hat{\underline{X}}_{\text{grad},T}^k$ and let, for the sake of brevity, $\underline{q}_T := \underline{E}_{\text{grad},T} \hat{\underline{q}}_T$. Owing to (6.5), for all $F \in \mathcal{F}_T$ we have $\hat{\underline{R}}_{\text{grad},F} \underline{q}_F = \hat{\underline{q}}_F$. Plugging this relation into the definition (5.37) of $\hat{\underline{R}}_{\mathcal{P},T}^{\ell_T} \underline{q}_T$ we find, for all $\mathbf{w}_T \in \mathcal{R}^{c,\ell_T+1}(T)$,

$$\int_T \hat{\underline{R}}_{\mathcal{P},T}^{\ell_T} \underline{q}_T \operatorname{div} \mathbf{w}_T = - \int_T \mathbf{G}_T^k \underline{q}_T \cdot \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{q}_F (\mathbf{w}_T \cdot \mathbf{n}_F) = \int_T E_{\mathcal{P},T}^{k-1} \hat{\underline{q}}_T \operatorname{div} \mathbf{w}_T,$$

where the conclusion comes from the definitions (4.4) of \mathbf{G}_T^k and (5.32) of $\underline{E}_{\text{grad},T}$. Recalling that $\operatorname{div} : \mathcal{R}^{c,\ell_T+1}(T) \rightarrow \mathcal{P}^{\ell_T}(T)$ is an isomorphism and applying (6.5) for $P = T$ yields $\hat{\underline{R}}_{\mathcal{P},T}^{\ell_T} \underline{q}_T = \hat{\underline{q}}_T$. This proves that $\hat{\underline{R}}_{\text{grad},h} \underline{E}_{\text{grad},h} = \operatorname{Id}$ on the whole of $\hat{\underline{X}}_{\text{grad},T}^k$.

(ii) *Proof of (A2).* The polynomial consistency is only meaningful for the local complex on a mesh element $T \in \mathcal{T}_h$, for which it is simply (6.2) with $P = T$.

(iii) *Proof of (C2).* Take $\underline{q}_h \in \ker \underline{\mathbf{G}}_h^k$. We claim that $\underline{E}_{\text{grad},T} \hat{\underline{R}}_{\text{grad},T} \underline{q}_T = \underline{q}_T$ for all $T \in \mathcal{T}_h$, which establishes a stronger version of (C2) (namely, $\underline{E}_{\text{grad},h} \hat{\underline{R}}_{\text{grad},h} - \text{Id} = 0$ on $\ker \underline{\mathbf{G}}_h^k$). The condition $\underline{\mathbf{G}}_h^k \underline{q}_h = \underline{0}$ implies $\underline{\mathbf{G}}_T^k \underline{q}_T = \underline{0}$ for all $T \in \mathcal{T}_h$ and thus, by exactness of the DDR sequence on T , $\underline{q}_T = \underline{I}_{\text{grad},T}^k M$ for some $M \in \mathbb{R}$. The property (A2) then yields $\underline{E}_{\text{grad},T} \hat{\underline{R}}_{\text{grad},T} \underline{q}_T = \underline{q}_T$ as claimed.

(iv) *Proof of (C3).* For this slice of the complex between \mathbb{R} and $\underline{X}_{\text{grad},h}^k$, we have $E_i = \hat{R}_i = \text{Id}_{\mathbb{R}}$ and the operators in the sequences are $\underline{I}_{\text{grad},h}^k$ and $\hat{\underline{I}}_{\text{grad},h}^k$. The fact that the reductions are cochain maps then follows from the definition (2.4) of $\hat{\underline{I}}_{\text{grad},h}^k$, while the cochain map property of the extension is simply (A2), proved above, applied to constant polynomials.

(iv) *Proof of (A1).* For all $T \in \mathcal{T}_h$, the continuity of $\hat{\underline{R}}_{\text{grad},T} : \underline{X}_{\text{grad},T}^k \rightarrow \hat{\underline{X}}_{\text{grad},T}^k$ is a direct consequence of the norm equivalences in $\underline{X}_{\text{grad},T}^k$ and $\hat{\underline{X}}_{\text{grad},T}^k$ (see [14, Lemma 5] and Lemma 19), the boundedness of the L^2 -projector $\pi_{\mathcal{P},F}^{\ell_F}$, and, to estimate $\hat{\underline{R}}_{\mathcal{P},T}^{\ell_T} \underline{q}_T$, [14, Lemma 9] and the continuities (4.5) of $\underline{\mathbf{G}}_T^k$ and [14, Eq. (4.22)] of γ_F^{k+1} .

(iv) *Proof of (A3).* This property on the original DDR complex is proved in [14, Lemma 6]. \square

6.4 Homological and analytical properties for the curl

The goal of this section is to prove homological and analytical properties for the curl. We remind the reader that, according to (2.2),

$$\hat{\underline{\mathbf{G}}}_h^k := \hat{\underline{\mathbf{R}}}_{\text{curl},h} \underline{\mathbf{G}}_h^k \underline{E}_{\text{grad},h} \quad \text{and} \quad \hat{\underline{\mathbf{C}}}_h^k := \hat{\underline{\mathbf{R}}}_{\text{div},h} \underline{\mathbf{C}}_h^k \underline{E}_{\text{curl},h}.$$

We start by addressing the cochain property for the reduction and extension maps.

Lemma 22 (Cochain property of the reduction). *For the slice of the complex between $\underline{X}_{\text{grad},h}^k$ and $\underline{X}_{\text{curl},h}^k$, property (C3) holds for the reduction, i.e.,*

$$\hat{\underline{\mathbf{G}}}_h^k \hat{\underline{R}}_{\text{grad},h} \underline{q}_h = \hat{\underline{\mathbf{R}}}_{\text{curl},h} \underline{\mathbf{G}}_h^k \underline{q}_h \quad \forall \underline{q}_h \in \underline{X}_{\text{grad},h}^k. \quad (6.13)$$

Proof. Let $\underline{q}_h \in \underline{X}_{\text{grad},h}^k$ and set, for the sake of brevity, $\hat{\underline{q}}_h := \hat{\underline{R}}_{\text{grad},h} \underline{q}_h$.

(i) *Gradient components on $\mathcal{R}^{c,\ell_P+1}(\mathcal{P})$.* We start by proving the following result: For all $\mathcal{P} \in \mathcal{T}_h \cup \mathcal{F}_h$,

$$\pi_{\mathcal{R},\mathcal{P}}^{c,\ell_P+1} \underline{\mathbf{G}}_{\mathcal{P}}^k \underline{E}_{\text{grad},\mathcal{P}} \hat{\underline{R}}_{\text{grad},\mathcal{P}} \underline{q}_{\mathcal{P}} = \pi_{\mathcal{R},T}^{c,\ell_P+1} \underline{\mathbf{G}}_{\mathcal{P}}^k \underline{q}_{\mathcal{P}} \quad \forall \underline{q}_{\mathcal{P}} \in \underline{X}_{\text{grad},\mathcal{P}}^k. \quad (6.14)$$

We detail the proof for the case $\mathcal{P} = T \in \mathcal{T}_h$, the case $\mathcal{P} = F \in \mathcal{F}_h$ being similar. Owing to (6.6) and (3.3) with $\ell = \ell_T$, we only have to prove that $\pi_{\mathcal{R},T}^{c,\ell_T+1} \underline{\mathbf{S}}_{\text{grad},T}^k \hat{\underline{q}}_T = \pi_{\mathcal{R},T}^{c,\ell_T+1} \underline{\mathbf{G}}_T^k \underline{q}_T$. This relation can be established taking $(\tau, \mu) = (\mathbf{0}, \mathbf{w}_T)$ with $\mathbf{w}_T \in \mathcal{R}^{c,\ell_T+1}(T)$ as a test function in the problem defining $\underline{\mathbf{S}}_{\text{grad},T}^k \hat{\underline{q}}_T$ (i.e., (5.26) with $\mathcal{L}_T = \mathcal{L}_{\text{grad},T}$ given by (5.28)) to write

$$\int_T \underline{\mathbf{S}}_{\text{grad},T}^k \hat{\underline{q}}_T \cdot \mathbf{w}_T = - \int_T \hat{\underline{R}}_{\mathcal{P},T}^{\ell_T} \underline{q}_T \text{div } \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_F^{k+1} \underline{E}_{\text{grad},F} \hat{\underline{q}}_F (\mathbf{w}_T \cdot \mathbf{n}_F) \stackrel{(5.37)}{=} \int_T \underline{\mathbf{G}}_T^k \underline{q}_T \cdot \mathbf{w}_T.$$

(ii) *Cochain property of the reduction.* The components of $\underline{E}_{\text{grad},h} \hat{\underline{q}}_h$ and \underline{q}_h on the mesh edge skeleton coincide, and thus so do their edge gradient as well as the components of their discrete gradients on $\mathcal{R}^{k-1}(F)$, $F \in \mathcal{F}_h$ (depending only on the skeletal components). By definition of $\hat{\underline{\mathbf{R}}}_{\text{curl},h}$, this shows that the equality in (6.13) holds for these components. The equality of the components on $\mathcal{R}^{c,\ell_F+1}(F)$, $F \in \mathcal{F}_h$, is an immediate consequence of (6.14) for $\mathcal{P} = F$.

Let now $T \in \mathcal{T}_h$. We have just proved that, for all $F \in \mathcal{F}_T$, $\hat{\mathbf{G}}_F^k \hat{q}_F = \hat{\mathbf{R}}_{\text{curl},F} \mathbf{G}_F^k q_F$. By [14, Remark 15], we have $\mathbf{C}_T^k \mathbf{G}_T^k = \mathbf{0}$. Hence, the definition (5.38) of $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1}$ applied to $\underline{v}_T = \mathbf{G}_T^k \underline{E}_{\text{grad},T} \hat{q}_T$ and $\underline{v}_T = \mathbf{G}_T^k q_T$ shows that the components of each side of (6.13) on $\mathcal{R}^{k-1}(T)$ coincide. The equality of the components on $\mathcal{R}^{c,\ell_T+1}(T)$, $T \in \mathcal{T}_h$, is an immediate consequence of (6.14). \square

Lemma 23 (Cochain property of the extension). *For the slice of the complex between $\underline{X}_{\text{grad},T}^k$ and $\underline{X}_{\text{curl},T}^k$, property (C3) holds for the extensions, i.e.,*

$$\underline{E}_{\text{curl},h} \hat{\mathbf{G}}_h^k \hat{q}_h = \underline{G}_h^k \underline{E}_{\text{grad},h} \hat{q}_h \quad \forall \hat{q}_h \in \hat{X}_{\text{grad},h}^k. \quad (6.15)$$

Proof. Given that $\underline{E}_{\text{curl},h}$ and $\hat{\mathbf{R}}_{\text{curl},h}$ leave the components on $\mathcal{P}^k(E)$, $E \in \mathcal{E}_h$, and $\mathcal{R}^{k-1}(F)$, $F \in \mathcal{F}_h$, unchanged, the equality of these components on each side of (6.15) is trivial. For $F \in \mathcal{F}_h$ we have, owing to (6.9) and (6.6) for $P = F$,

$$\pi_{\mathcal{R},F}^{c,k} \mathbf{S}_{\text{curl},F}^k \hat{\mathbf{G}}_F^k \hat{q}_F = \pi_{\mathcal{R},F}^{c,k} \mathbf{S}_{\text{grad},F}^k \hat{q}_F = \pi_{\mathcal{R},F}^{c,k} \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{q}_F,$$

which proves that the components on $\mathcal{R}^{c,k}(F)$ of each side of (6.15) also coincide, so that

$$\underline{E}_{\text{curl},F} \hat{\mathbf{G}}_F^k \hat{q}_F = \underline{E}_{\text{curl},F} \hat{\mathbf{R}}_{\text{curl},F} \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{q}_F = \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{q}_F \quad \forall F \in \mathcal{F}_T. \quad (6.16)$$

With the same approach, using (6.9) and (6.6) for $P = T \in \mathcal{T}_h$, we show that the components on $\mathcal{R}^{c,k}(T)$ also coincide. It remains to analyse, for $T \in \mathcal{T}_h$, the components on $\mathcal{R}^{k-1}(T)$. Setting $\underline{v}_T := \mathbf{G}_T^k \underline{E}_{\text{grad},T} \hat{q}_T$, this component for the left-hand side of (6.15) is $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{v}_T$ given by (5.38). Plugging into this expression $\mathbf{C}_T^k \underline{v}_T = \mathbf{0}$ (consequence of [14, Remark 15]), using (6.16) to write $\underline{E}_{\text{curl},F} \hat{\mathbf{R}}_{\text{curl},F} \underline{v}_F = \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{q}_F$, using [14, Eq. (3.26)] to write $\gamma_{t,F}^k \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{q}_F = \mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{q}_F$, and recalling the link between element and face gradients expressed by [14, Eq. (3.17)], we infer that,

$$\int_T \hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{v}_T \cdot \text{curl } w_T = \int_T \mathbf{G}_T^k \underline{E}_{\text{grad},T} \hat{q}_T \cdot \text{curl } w_T \quad \forall w_T \in \mathcal{G}^{c,k}(T),$$

which proves the equality of the components on $\mathcal{R}^{k-1}(T)$ of each side of (6.15). \square

The following intermediate result will be used to establish (C2), as well as (C3) for the last part of the complex involving $\underline{X}_{\text{div},h}^k$.

Lemma 24 (Relation among \underline{C}_h^k , $\underline{E}_{\text{curl},h}$, and $\hat{\mathbf{R}}_{\text{curl},h}$). *It holds*

$$\underline{C}_h^k \underline{E}_{\text{curl},h} \hat{\mathbf{R}}_{\text{curl},h} \underline{v}_h = \underline{C}_h^k \underline{v}_h \quad \forall \underline{v}_h \in \underline{X}_{\text{curl},h}^k. \quad (6.17)$$

Proof. Let $\underline{v}_h \in \underline{X}_{\text{curl},h}^k$ and set, for the sake of brevity, $\hat{\underline{v}}_h := \hat{\mathbf{R}}_{\text{curl},h} \underline{v}_h$. The components of \underline{v}_h and $\underline{E}_{\text{curl},h} \hat{\underline{v}}_h$ on $\mathcal{P}^k(E)$, $E \in \mathcal{E}_h$, and on $\mathcal{R}^{k-1}(F)$, $F \in \mathcal{F}_h$, coincide. Since the face curls only depend on these components, we infer that $C_F^k \underline{E}_{\text{curl},F} \hat{\underline{v}}_F = C_F^k \underline{v}_F$ for all $F \in \mathcal{F}_h$. The link between full curl and face curls given in [14, Proposition 4] then shows that $\pi_{\mathcal{G},T}^{k-1} \mathbf{C}_T^k \underline{E}_{\text{curl},T} \hat{\underline{v}}_T = \pi_{\mathcal{G},T}^{k-1} \mathbf{C}_T^k \underline{v}_T$ for all $T \in \mathcal{T}_h$. We have therefore proved that the components on the faces and on $\mathcal{G}^{k-1}(T)$, $T \in \mathcal{T}_h$, of both sides of (6.17) coincide. Let now $T \in \mathcal{T}_h$ and consider the components of the discrete curls on $\mathcal{G}^{c,k}(T)$. By definition (5.33) of $\underline{E}_{\text{curl},T}$, the component of $\underline{E}_{\text{curl},T} \hat{\underline{v}}_T$ on $\mathcal{R}^{k-1}(T)$ is that of $\hat{\underline{v}}_T$, which

is $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T$ given by (5.38). The definitions (4.7) of $\mathbf{C}_T^k \underline{\mathbf{E}}_{\text{curl},T} \hat{\underline{\mathbf{v}}}_T$ and (5.38) of $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T$ then give, for all $\mathbf{w}_T \in \mathcal{G}^{c,k}(T)$,

$$\begin{aligned} & \int_T \mathbf{C}_T^k \underline{\mathbf{E}}_{\text{curl},T} \hat{\underline{\mathbf{v}}}_T \cdot \mathbf{w}_T \\ &= \int_T \hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T \cdot \mathbf{curl} \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_{\iota,F}^k \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{v}}}_F \cdot (\mathbf{w}_T \times \mathbf{n}_F) = \int_T \mathbf{C}_T^k \underline{\mathbf{v}}_T \cdot \mathbf{w}_T. \end{aligned}$$

This implies that $\pi_{\mathcal{G},T}^{c,k} \mathbf{C}_T^k \underline{\mathbf{E}}_{\text{curl},T} \hat{\underline{\mathbf{v}}}_T = \pi_{\mathcal{G},T}^{c,k} \mathbf{C}_T^k \underline{\mathbf{v}}_T$ and concludes the proof. \square

Lemma 25 (Properties of the serendipity curl space). *The serendipity construction for the curl space satisfies both the homological properties of Assumption 1 and the analytical properties of Assumption 3, with continuity constants in (A1) and (A3) that do not depend on h .*

Proof. (i) *Proof of (C1).* Let $F \in \mathcal{F}_h$ and $\hat{\underline{\mathbf{v}}}_F \in \hat{\mathbf{X}}_{\text{curl},F}^k$. By (6.7) with $\mathbb{P} = F$, we have $\pi_{\mathcal{R},F}^{c,\ell_F+1} \mathbf{S}_{\text{curl},F}^k \hat{\underline{\mathbf{v}}}_F = \hat{\underline{\mathbf{v}}}_{\mathcal{R},F}^c$. Combined with the definition (5.24) of $\hat{\underline{\mathbf{R}}}_{\text{curl},F}$ with $\underline{\mathbf{v}}_F = \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{v}}}_F$ and (3.3), this gives

$$\forall F \in \mathcal{F}_h, \quad \hat{\underline{\mathbf{R}}}_{\text{curl},F} \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{v}}}_F = \hat{\underline{\mathbf{v}}}_F \quad \forall \hat{\underline{\mathbf{v}}}_F \in \hat{\mathbf{X}}_{\text{curl},F}^k, \quad (6.18)$$

the equality of the components on $\mathcal{P}^k(E)$, $E \in \mathcal{E}_F$, and $\mathcal{R}^{k-1}(F)$ being trivial as these are not affected by the restriction/extension operators.

Take now $\hat{\underline{\mathbf{v}}}_h \in \hat{\mathbf{X}}_{\text{curl},h}^k$ and set, for the sake of brevity, $\underline{\mathbf{v}}_h := \underline{\mathbf{E}}_{\text{curl},h} \hat{\underline{\mathbf{v}}}_h$. For all $T \in \mathcal{T}_h$, invoking (6.18) and using again (6.7) and (3.3) gives

$$\hat{\underline{\mathbf{R}}}_{\text{curl},T} \underline{\mathbf{v}}_T = (\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T, \hat{\underline{\mathbf{v}}}_{\mathcal{R},T}^c, (\hat{\underline{\mathbf{v}}}_{\mathcal{R},F}, \hat{\underline{\mathbf{v}}}_{\mathcal{R},F}^c)_{F \in \mathcal{F}_T}, (\hat{\underline{\mathbf{v}}}_E)_{E \in \mathcal{E}_T}).$$

According to its definition (5.38), $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T \in \mathcal{R}^{k-1}(T)$ satisfies, for all $\mathbf{w}_T \in \mathcal{G}^{c,k}(T)$,

$$\int_T \hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T \cdot \mathbf{curl} \mathbf{w}_T = \int_T \mathbf{C}_T^k \underline{\mathbf{v}}_T \cdot \mathbf{w}_T - \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \gamma_{\iota,F}^k \underline{\mathbf{v}}_F \cdot (\mathbf{w}_T \times \mathbf{n}_F) = \int_T \hat{\underline{\mathbf{v}}}_{\mathcal{R},T} \cdot \mathbf{curl} \mathbf{w}_T,$$

where we have used (6.18) to write $\gamma_{\iota,F}^k \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{R}}}_{\text{curl},F} \underline{\mathbf{v}}_F = \gamma_{\iota,F}^k \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{R}}}_{\text{curl},F} \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{v}}}_F = \gamma_{\iota,F}^k \underline{\mathbf{E}}_{\text{curl},F} \hat{\underline{\mathbf{v}}}_F = \gamma_{\iota,F}^k \underline{\mathbf{v}}_F$ and concluded using the definition (4.7) of \mathbf{C}_T^k together with the fact that the component of $\underline{\mathbf{v}}_T = \underline{\mathbf{E}}_{\text{curl},T} \hat{\underline{\mathbf{v}}}_T$ on $\mathcal{R}^{k-1}(T)$ is $\hat{\underline{\mathbf{v}}}_{\mathcal{R},T}$. Since $\mathbf{curl} : \mathcal{G}^{c,k}(T) \rightarrow \mathcal{R}^{k-1}(T)$ is onto, this gives $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T = \hat{\underline{\mathbf{v}}}_{\mathcal{R},T}$, concluding the proof of a stronger property than (C1), namely $\hat{\underline{\mathbf{R}}}_{\text{curl},h} \underline{\mathbf{E}}_{\text{curl},h} = \text{Id}$ on the whole of $\hat{\mathbf{X}}_{\text{curl},h}^k$.

(ii) *Proof of (C2).* Let $\underline{\mathbf{v}}_h \in \ker \underline{\mathbf{C}}_h^k$ and set $\hat{\underline{\mathbf{v}}}_h := \hat{\underline{\mathbf{R}}}_{\text{curl},h} \underline{\mathbf{v}}_h$. By (6.17), the vector

$$\begin{aligned} \underline{\mathbf{E}}_{\text{curl},h} \hat{\underline{\mathbf{v}}}_h - \underline{\mathbf{v}}_h &= ((\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \underline{\mathbf{v}}_T - \underline{\mathbf{v}}_{\mathcal{R},T}, \pi_{\mathcal{R},T}^{c,k} \mathbf{S}_{\text{curl},T}^k \hat{\underline{\mathbf{v}}}_T - \underline{\mathbf{v}}_{\mathcal{R},T}^c)_{T \in \mathcal{T}_h}, \\ & \quad (\mathbf{0}, \pi_{\mathcal{R},F}^{c,k} \mathbf{S}_{\text{curl},F}^k \hat{\underline{\mathbf{v}}}_F - \underline{\mathbf{v}}_{\mathcal{R},F}^c)_{F \in \mathcal{F}_h}, \\ & \quad (\mathbf{0})_{E \in \mathcal{E}_h}) \end{aligned} \quad (6.19)$$

belongs to $\ker \underline{\mathbf{C}}_h^k$. By local exactness, for all $T \in \mathcal{T}_h$ we therefore have $\underline{\mathbf{E}}_{\text{curl},T} \hat{\underline{\mathbf{v}}}_T - \underline{\mathbf{v}}_T = \underline{\mathbf{G}}_T^k \underline{\mathbf{q}}_T$ for some $\underline{\mathbf{q}}_T \in \underline{\mathbf{X}}_{\text{grad},T}^k$ that is constant on the edge skeleton of T (since its derivative there vanishes by (6.19)). We can therefore assume, possibly after translation, that $\underline{\mathbf{q}}_{\mathcal{E}_T} = 0$. Moreover, for all $F \in \mathcal{F}_h$, by definition (4.3) of $\underline{\mathbf{G}}_F^k$, $\underline{\mathbf{q}}_F \in \mathcal{P}^{k-1}(F)$ is entirely and uniquely fixed by the component $\pi_{\mathcal{R},F}^{c,k} \underline{\mathbf{G}}_F^k \underline{\mathbf{q}}_F$ of

$\underline{G}_T^k \underline{q}_T$ on $\mathcal{R}^{c,k}(F)$ (and the zero edge value of \underline{q}_T), which is $\pi_{\mathcal{R},F}^{c,k} \mathbf{S}_{\text{curl},F}^k \hat{\mathbf{v}}_F - \mathbf{v}_{\mathcal{R},F}^c$ by (6.19); hence, \underline{q}_F matches between neighbouring elements. This enables us to trivially glue together all the \underline{q}_T in each element into a vector $\underline{q}_h \in \underline{X}_{\text{grad},h}^k$ that satisfies $\underline{E}_{\text{curl},h} \hat{\mathbf{v}}_h - \mathbf{v}_h = \underline{G}_h^k \underline{q}_h$, which concludes the proof of (C2).

(iii) *Proof of (C3).* This property is established in Lemmas 22 and 23.

(iv) *Proof of (A1).* The continuity of $\hat{\mathbf{R}}_{\text{curl},T}$ is proved in a similar way as that of $\hat{\mathbf{R}}_{\text{grad},T}$, using Lemma 19, the norm equivalence in $\underline{X}_{\text{curl},T}^k$ stated in [14, Lemma 5], and the continuity of \mathbf{C}_T^k stated in [15, Proposition 13].

(v) *Proof of (A2).* This property is only meaningful for the local complex on a mesh element $T \in \mathcal{T}_h$, for which it is simply (6.4) for $\mathbf{P} = T$.

(iv) *Proof of (A3).* This property is proved in [14, Lemma 6]. □

6.5 Divergence space

As mentioned in Remark 10, no serendipity reduction of DOFs is performed on $\underline{X}_{\text{div},h}^k$. Hence, $\underline{E}_{\text{div},T} = \hat{\mathbf{R}}_{\text{div},T} = \text{Id}_{\underline{X}_{\text{div},T}^k}$ and (C1), (C2), (A1), and (A2) are trivially satisfied. Regarding (C3), the co-chain property of the reduction follows from (6.17), while that of the extension is simply due to the definition 2.2 of $\hat{\mathbf{C}}_h^k$. The property (A3) is proved in [14, Lemma 6].

Reducing the number of DOFs in discrete spaces associated with the divergence operator is actually technically quite challenging, as already noticed in [9]. However, we argue here that such a reduction is simply not possible if one wants to preserve even only two (important) properties of the discrete complex, namely the commutation property of Proposition 7 and the local exactness property.

Let $T \in \mathcal{T}_h$. The definition (4.8) of D_T^k shows that this operator depends on the components on $\mathcal{P}^k(F)$, $F \in \mathcal{F}_T$, and $\mathcal{G}^{k-1}(T)$ of $\underline{X}_{\text{div},T}^k$. To preserve the commutation property, only the component $\mathcal{G}^{c,k}(T)$ can therefore be reduced (as already noticed in [9] in the context of VEM spaces). A candidate for the local serendipity space would therefore be: For some $m_T < k - 1$,

$$\begin{aligned} \hat{\underline{X}}_{\text{div},T}^k &:= \left\{ \underline{\mathbf{w}}_T = (\mathbf{w}_{\mathcal{G},T}, \mathbf{w}_{\mathcal{G},T}^c, (w_F)_{F \in \mathcal{F}_h}) : \right. \\ &\quad \left. \mathbf{w}_{\mathcal{G},T} \in \mathcal{G}^{k-1}(T) \text{ and } \mathbf{w}_{\mathcal{G},T}^c \in \mathcal{G}^{c,m_T+1}(T), \text{ and } w_F \in \mathcal{P}^k(F) \text{ for all } F \in \mathcal{F}_T \right\}, \end{aligned}$$

with reduction operator $\hat{\mathbf{R}}_{\text{div},T} : \underline{X}_{\text{div},T}^k \rightarrow \hat{\underline{X}}_{\text{div},T}^k$ defined by

$$\hat{\mathbf{R}}_{\text{div},T} \underline{\mathbf{w}}_T = (\mathbf{w}_{\mathcal{G},T}, \pi_{\mathcal{G},T}^{c,m_T+1} \mathbf{w}_{\mathcal{G},T}^c, (w_F)_{F \in \mathcal{F}_T}) \quad \forall \underline{\mathbf{w}}_T \in \underline{X}_{\text{div},T}^k.$$

However, such a choice would lead to a defect of the exactness property of the complex, specifically:

$$\ker \hat{\mathbf{C}}_T^k \not\subset \text{Im } \hat{\mathbf{G}}_T^k. \quad (6.20)$$

Let us clearly demonstrate this. Since $m_T < k - 1$, we can find $\hat{\mathbf{v}}_{\mathcal{R},T} \in \mathcal{R}^{k-1}(T)$ such that $\hat{\mathbf{v}}_{\mathcal{R},T} \neq \mathbf{0}$ and $\hat{\mathbf{v}}_{\mathcal{R},T}$ is orthogonal to $\mathcal{R}^{m_T}(T)$ for the L^2 -inner product. Set $\hat{\mathbf{v}}_T := (\hat{\mathbf{v}}_{\mathcal{R},T}, \mathbf{0}, (\mathbf{0}, \mathbf{0})_{F \in \mathcal{F}_T}, (0)_{E \in \mathcal{E}_T}) \in \hat{\underline{X}}_{\text{curl},T}^k$ and let $\underline{\mathbf{v}}_T := \underline{E}_{\text{curl},T} \hat{\mathbf{v}}_T$. We prove (6.20) by showing that

$$\hat{\mathbf{C}}_T^k \hat{\mathbf{v}}_T := \hat{\mathbf{R}}_{\text{div},T} \mathbf{C}_T^k \underline{\mathbf{v}}_T = \mathbf{0} \quad \text{and} \quad \hat{\mathbf{v}}_T \notin \text{Im } \hat{\mathbf{G}}_T^k. \quad (6.21)$$

We first notice that $\mathbf{C}_F^k \underline{\mathbf{v}}_F = \mathbf{0}$ for all $F \in \mathcal{F}_T$, since all face and edge components of $\underline{\mathbf{v}}_T$ are equal zero. The link between element and face discrete curls of [14, Proposition 4] then shows that $\pi_{\mathcal{G},T}^{k-1} \mathbf{C}_T^k \underline{\mathbf{v}}_T = \mathbf{0}$.

It remains to prove that the component of $\hat{\mathbf{R}}_{\text{div},T}^k \mathbf{C}_T^k \underline{\mathbf{v}}_T$ on $\mathcal{G}^{c,m_T+1}(T)$ vanishes. Since $m_T + 1 < k$, this component is $\pi_{\mathcal{G},T}^{c,m_T+1} \mathbf{C}_T^k \underline{\mathbf{v}}_T$. Since $\underline{\mathbf{v}}_F = \underline{\mathbf{0}}$ for all $F \in \mathcal{F}_T$, the definition (4.7) of \mathbf{C}_T^k yields

$$\int_T \mathbf{C}_T^k \underline{\mathbf{v}}_T \cdot \mathbf{z}_T = \int_T \hat{\mathbf{v}}_{\mathcal{R},T} \cdot \mathbf{curl} \mathbf{z}_T = 0 \quad \forall \mathbf{z}_T \in \mathcal{G}^{c,m_T+1}(T),$$

where we have used in the first equality $\mathbf{v}_{\mathcal{R},T} = \hat{\mathbf{v}}_{\mathcal{R},T}$ (see (5.33)) and, to conclude, the orthogonality of $\hat{\mathbf{v}}_{\mathcal{R},T}$ and $\mathcal{R}^{m_T}(T)$. This proves the first relation in (6.21).

We prove the second relation by contradiction. Assume that $\hat{\underline{\mathbf{v}}}_T = \hat{\mathbf{G}}_T^k \hat{\underline{\mathbf{q}}}_T$ for some $\hat{\underline{\mathbf{q}}}_T \in \hat{\mathcal{X}}_{\text{grad},T}^k$. This gives, for all $F \in \mathcal{F}_T$, $\hat{\mathbf{G}}_F^k \hat{\underline{\mathbf{q}}}_F = \underline{\mathbf{v}}_F = \underline{\mathbf{0}}$ and thus, by the cochain property (C3), $\mathbf{G}_F^k \underline{E}_{\text{grad},F} \hat{\underline{\mathbf{q}}}_F = \underline{E}_{\text{curl},F} \hat{\mathbf{G}}_F^k \hat{\underline{\mathbf{q}}}_F = \underline{\mathbf{0}}$. Using the definition (5.38) of $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1}$ together with $\mathbf{C}_T^k \mathbf{G}_T^k = \underline{\mathbf{0}}$ (see [14, Remark 15]), we deduce that $\hat{\mathbf{R}}_{\mathcal{R},T}^{k-1} \mathbf{G}_T^k \underline{E}_{\text{grad},T} \hat{\underline{\mathbf{q}}}_T = \underline{\mathbf{0}}$. Since $\hat{\mathbf{G}}_T^k \hat{\underline{\mathbf{q}}}_T = \hat{\underline{\mathbf{v}}}_T$, this condition implies $\hat{\mathbf{v}}_{\mathcal{R},T} = \underline{\mathbf{0}}$, which contradicts our choice of $\hat{\mathbf{v}}_{\mathcal{R},T}$.

6.6 Homological and analytical properties of the SDDR complex and numerical tests

Lemmas 21 and 25 show that the SDDR complex at the bottom of Diagram (5.1) as well as its global counterpart fulfil Assumptions 1 and 3. The results in Section 2 thus show that all the relevant properties of the original DDR complex proved in [14, Sections 5 and 6] transfer to its serendipity counterpart.

A consequence of the above remark is that the numerical scheme for magnetostatics obtained replacing the space $\mathcal{X}_{\text{curl},h}^k$ with its serendipity version $\hat{\mathcal{X}}_{\text{curl},h}^k$ in [14, Section 7] has analogous convergence properties as the original one (see [14, Theorem 12] for a precise statement of an error estimate). To assess the possible difference in practical accuracy and the gain resulting from the use of the serendipity space, we therefore compare the original DDR and the SDDR schemes on the numerical example of [14, Section 7.3], for polynomial degrees $k = 1, 2, 3$ (no DOF reduction is achieved for the lowest order degree $k = 0$, which is therefore removed from our comparison). Both schemes are implemented within the open-source HARDCore3D C++ framework (see <https://github.com/jdroniou/HARDCore>), using standard C++ multi-threading routines and linear algebra facilities from the Eigen3 library (see <http://eigen.tuxfamily.org>). All tests were performed on a Dell Precision 5820 desktop with a 14-core Intel Xeon processor (W-2275) clocked at 3.3GHz and equipped with 128Gb of DDR4 RAM, running Ubuntu 20.04.4 LTS.

A comparison of the corresponding discrete errors as functions of the mesh size for the ‘‘Tetgen-Cube-0’’ (matching simplicial) and ‘‘Voro-small-0’’ (Voronoi) mesh families available in the HARDCore3D repository is provided in Fig. 1, showing that the accuracies of DDR and SDDR are almost identical and that both methods achieve optimal rates of convergence, irrespectively of the considered mesh and polynomial degree.

The (processor and wall) CPU times for the resolution the linear systems (after static condensation of the remaining element unknowns) through the MKL PARDISO solver (see <https://software.intel.com/en-us/mkl>) are depicted in Fig. 2. The observed gain is significant: for $k = 3$ on the finest ‘‘Voro-small-0’’ mesh, e.g., a 40% reduction of the solution processor time is observed for the SDDR scheme, translating into a 45% reduction of the wall time (626s vs. 1145s). A comparison of the assembly wall and processor times, not reported here for the sake of conciseness, also confirms that, being an embarrassingly parallel step, assembly can fully benefit from shared-memory parallelism and that the additional calculations required for the serendipity spaces form a negligible portion of that assembly time.

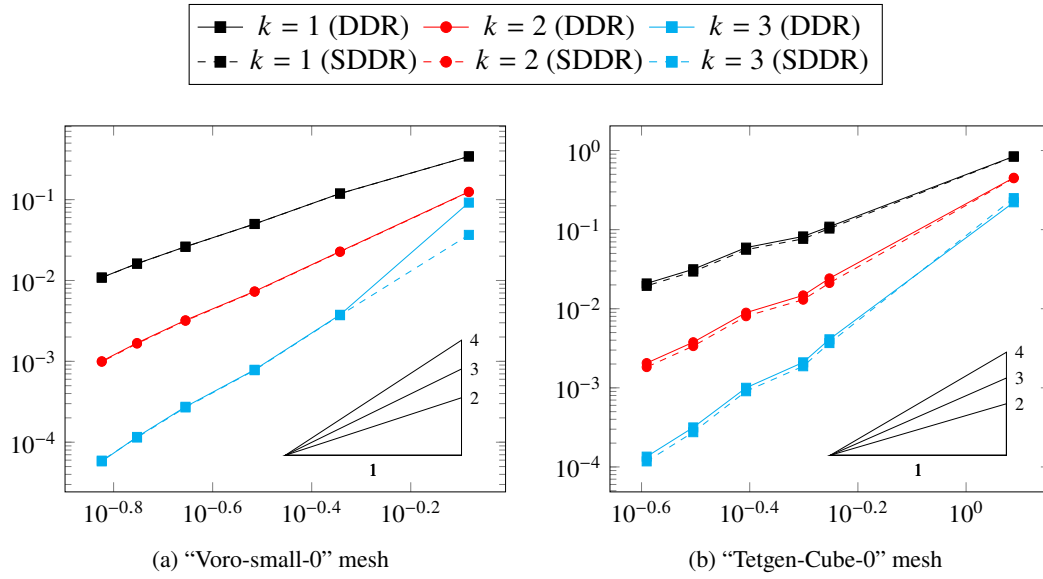


Figure 1: Relative errors in the discrete $H(\text{curl}; \Omega) \times H(\text{div}; \Omega)$ norm vs. h , for the standard DDR scheme (continuous lines), and the SDDR scheme (dashed lines).

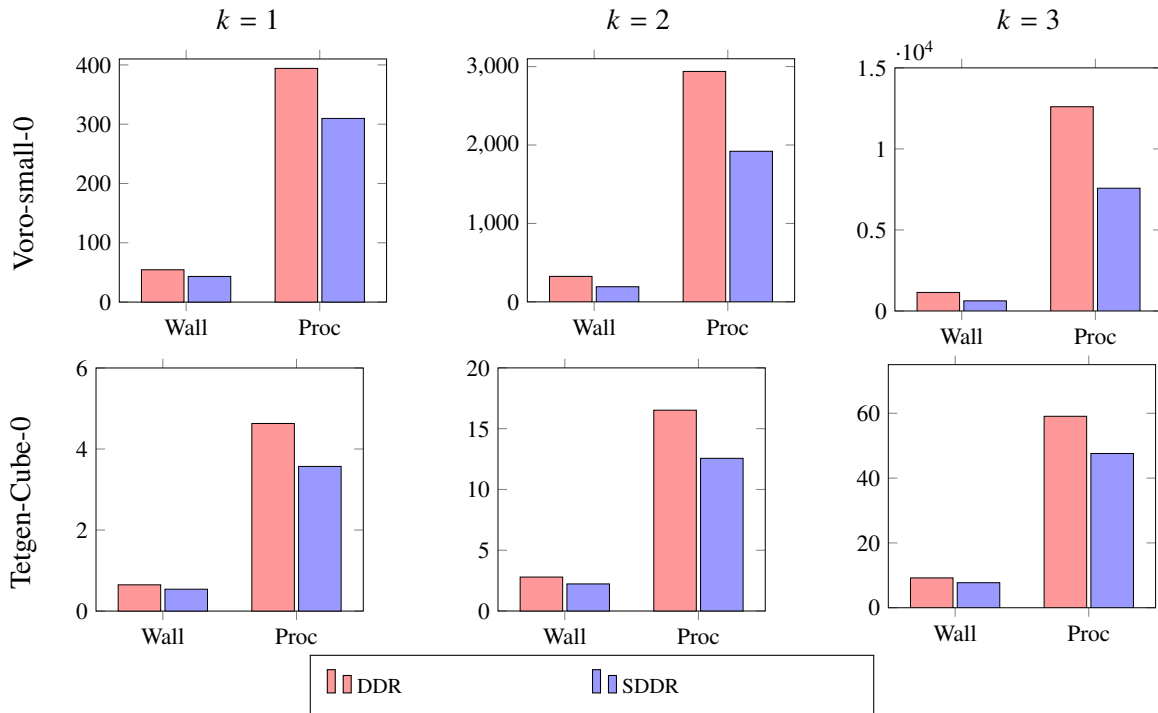


Figure 2: Wall and processor times (in seconds) for the resolution of the linear system for the DDR and SDDR methods. Times correspond to the finest mesh of each sequence.

A Estimates of polynomials from boundary values

A.1 Proof of Lemma 13

Let $q \in \mathcal{P}^{k+1}(\mathbb{P})$ and let us list the elements of $\mathcal{B}_{s,\mathbb{P}}$ as $\mathbf{b}_1, \dots, \mathbf{b}_{\eta_{\mathbb{P}}}$. We will construct by induction polynomials $(q_i)_{i=1, \dots, \eta_{\mathbb{P}}}$ and $(\tilde{q}_i)_{i=1, \dots, \eta_{\mathbb{P}}}$ such that, for all $i = 1, \dots, \eta_{\mathbb{P}}$,

$$\begin{aligned} q &= q_1 + \text{dist}_{\mathbb{P}\mathbf{b}_1} q_2 + \dots + (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_{i-1}}) q_i + (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_i}) \tilde{q}_i, \\ q_i &\in \mathcal{P}^{k+1-(i-1)}(\mathbb{P}), \quad \tilde{q}_i \in \mathcal{P}^{k+1-i}(\mathbb{P}), \quad \|q_i\|_{\mathbb{P}} \lesssim h_{\mathbb{P}}^{1/2} (\|q_{|\mathbf{b}_1}\|_{\mathbf{b}_1} + \dots + \|q_{|\mathbf{b}_i}\|_{\mathbf{b}_i}). \end{aligned} \quad (\text{A.1})$$

Let us first consider $i = 1$. We can easily extend $q_{|\mathbf{b}_1}$ (e.g. by making it independent of the normal coordinate to \mathbf{b}_1) as a polynomial $q_1 \in \mathcal{P}^{k+1}(\mathbb{P})$ such that $\|q_1\|_{\mathbb{P}} \lesssim h_{\mathbb{P}}^{1/2} \|q_{|\mathbf{b}_1}\|_{\mathbf{b}_1}$. Then, $q - q_1 \in \mathcal{P}^{k+1}(\mathbb{P})$ vanishes on \mathbf{b}_1 , and can thus be factorised by $\text{dist}_{\mathbb{P}\mathbf{b}_1} \in \mathcal{P}^1(\mathbb{P})$: there is $\tilde{q}_1 \in \mathcal{P}^k(\mathbb{P})$ such that $q - q_1 = \text{dist}_{\mathbb{P}\mathbf{b}_1} \tilde{q}_1$. This concludes the proof of (A.1) for $i = 1$.

Let us now take $j \leq \eta_{\mathbb{P}} - 1$ and show that this relation holds for $i = j + 1$ if it holds for $i = 1, \dots, j$. Since

$$|\text{dist}_{\mathbb{P}\mathbf{b}_r}| \lesssim 1 \quad \forall r = 1, \dots, \eta_{\mathbb{P}}, \quad (\text{A.2})$$

we have, by triangle inequality and the equality in (A.1) for $i = j$,

$$\begin{aligned} \|(\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_j})_{|\mathbf{b}_{j+1}} (\tilde{q}_j)_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} &\leq \|q_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} + \|(q_1)_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} + \dots + \|(q_j)_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} \\ &\lesssim \|q_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} + \|q_{|\mathbf{b}_1}\|_{\mathbf{b}_1} + \dots + \|q_{|\mathbf{b}_j}\|_{\mathbf{b}_j} \end{aligned} \quad (\text{A.3})$$

where the second line is obtained using discrete trace inequalities and the estimates in (A.1) for $i = 1, \dots, j$. Assumption 11 ensures that $0 \leq (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_j})_{|\mathbf{b}_{j+1}} \lesssim 1$, and that $(\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_j})_{|\mathbf{b}_{j+1}} \gtrsim 1$ on a ball in \mathbf{b}_{j+1} of radius $\gtrsim h_{\mathbf{b}_{j+1}}$. The arguments in the proof of [16, Lemma 1.25] then show that the norms $\|\cdot\|_{\mathbf{b}_{j+1}}$ and $\|(\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_j})_{|\mathbf{b}_{j+1}} \cdot\|_{\mathbf{b}_{j+1}}$ are equivalent on $\mathcal{P}^{k+1-j}(\mathbf{b}_{j+1})$, and we infer from (A.3) that

$$\|(\tilde{q}_j)_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} \lesssim \|q_{|\mathbf{b}_1}\|_{\mathbf{b}_1} + \dots + \|q_{|\mathbf{b}_j}\|_{\mathbf{b}_j} + \|q_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}}.$$

We then extend $(\tilde{q}_j)_{|\mathbf{b}_{j+1}}$ into $q_{j+1} \in \mathcal{P}^{k+1-j}(\mathbb{P})$ such that

$$\|q_{j+1}\|_{\mathbb{P}} \lesssim h_{\mathbb{P}}^{1/2} \|(\tilde{q}_j)_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}} \lesssim h_{\mathbb{P}}^{1/2} (\|q_{|\mathbf{b}_1}\|_{\mathbf{b}_1} + \dots + \|q_{|\mathbf{b}_{j+1}}\|_{\mathbf{b}_{j+1}})$$

and we note that, since $\tilde{q}_j - q_{j+1} \in \mathcal{P}^{k+1-j}(\mathbb{P})$ vanishes on \mathbf{b}_{j+1} , we can factorise this polynomial into $\tilde{q}_j - q_{j+1} = \text{dist}_{\mathbb{P}\mathbf{b}_{j+1}} \tilde{q}_{j+1}$ with $\tilde{q}_{j+1} \in \mathcal{P}^{k+1-j-1}(\mathbb{P})$, which concludes the proof of (A.1) for $i = j + 1$.

To conclude the proof of the lemma, we consider (A.1) with $i = \eta_{\mathbb{P}}$. A triangle inequality and the estimate stated in this relation, together with (A.2), give

$$\|q\|_{\mathbb{P}} \lesssim h_{\mathbb{P}}^{1/2} (\|q_{|\mathbf{b}_1}\|_{\mathbf{b}_1} + \dots + \|q_{|\mathbf{b}_{\eta_{\mathbb{P}}}}\|_{\mathbf{b}_{\eta_{\mathbb{P}}}}) + \|\tilde{q}_{\eta_{\mathbb{P}}}\|_{\mathbb{P}}. \quad (\text{A.4})$$

Multiplying the equality in (A.1) by $\tilde{q}_{\eta_{\mathbb{P}}}$ and integrating over \mathbb{P} yields

$$\begin{aligned} \int_{\mathbb{P}} (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_{\eta_{\mathbb{P}}}}) \tilde{q}_{\eta_{\mathbb{P}}}^2 &= \int_{\mathbb{P}} q \tilde{q}_{\eta_{\mathbb{P}}} - \int_{\mathbb{P}} q_1 \tilde{q}_{\eta_{\mathbb{P}}} - \dots - \int_{\mathbb{P}} (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_{\eta_{\mathbb{P}}-1}}) q_{\eta_{\mathbb{P}}} \tilde{q}_{\eta_{\mathbb{P}}} \\ &= \int_{\mathbb{P}} (\pi_{\mathcal{P}, \mathbb{P}}^{k+1-\eta_{\mathbb{P}}} q) \tilde{q}_{\eta_{\mathbb{P}}} - \int_{\mathbb{P}} q_1 \tilde{q}_{\eta_{\mathbb{P}}} - \dots - \int_{\mathbb{P}} (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_{\eta_{\mathbb{P}}-1}}) q_{\eta_{\mathbb{P}}} \tilde{q}_{\eta_{\mathbb{P}}}, \end{aligned}$$

where the second line follows from $\tilde{q}_{\eta_{\mathbb{P}}} \in \mathcal{P}^{k+1-\eta_{\mathbb{P}}}(\mathbb{P})$. Since $\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_{\eta_{\mathbb{P}}}}$ is nonnegative and, by mesh regularity assumption, $\gtrsim 1$ on a ball in \mathbb{P} of radius $\gtrsim h_{\mathbb{P}}$, we can use the arguments in the proof of [16, Lemma 1.25], (A.2) and Cauchy–Schwarz inequalities to get

$$\|\tilde{q}_{\eta_{\mathbb{P}}}\|_{\mathbb{P}}^2 \lesssim \int_{\mathbb{P}} (\text{dist}_{\mathbb{P}\mathbf{b}_1} \dots \text{dist}_{\mathbb{P}\mathbf{b}_{\eta_{\mathbb{P}}}}) \tilde{q}_{\eta_{\mathbb{P}}}^2 \lesssim \|\pi_{\mathcal{P}, \mathbb{P}}^{k+1-\eta_{\mathbb{P}}} q\|_{\mathbb{P}} \|\tilde{q}_{\eta_{\mathbb{P}}}\|_{\mathbb{P}} + \|q_1\|_{\mathbb{P}} \|\tilde{q}_{\eta_{\mathbb{P}}}\|_{\mathbb{P}} + \dots + \|q_{\eta_{\mathbb{P}}}\|_{\mathbb{P}} \|\tilde{q}_{\eta_{\mathbb{P}}}\|_{\mathbb{P}}.$$

Simplifying by $\|\tilde{q}_{\eta_{\mathbb{P}}}\|_{\mathbb{P}}$ gives an upper bound on this quantity which, plugged into (A.4) together with the estimates on $\|q_i\|_{\mathbb{P}}$ stated in (A.1) for $i = 1, \dots, \eta_{\mathbb{P}}$, concludes the proof of (5.2).

A.2 Proof of Lemma 14

We focus on the case $\mathbf{P} = T \in \mathcal{T}_h$, the case $\mathbf{P} = F \in \mathcal{F}_h$ being similar. Let $\mathbf{v} \in \mathcal{P}^k(T)$. We first prove that

$$h_T \|\mathbf{curl} \mathbf{v}\|_T \lesssim \|\pi_{\mathcal{R},T}^{k-2} \mathbf{v}\|_T + \left(\sum_{F \in \mathcal{F}_T} h_T \|\mathbf{v}_{t,F}\|_F^2 \right)^{1/2}. \quad (\text{A.5})$$

For all $\mathbf{w}_T \in \mathcal{P}^{k-1}(T)$, integrating by parts and introducing $\pi_{\mathcal{R},T}^{k-2}$ (owing to $\mathbf{curl} \mathbf{w}_T \in \mathcal{R}^{k-2}(T)$) gives

$$\int_T \mathbf{curl} \mathbf{v} \cdot \mathbf{w}_T = \int_T \pi_{\mathcal{R},T}^{k-2} \mathbf{v} \cdot \mathbf{curl} \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F \mathbf{v}_{t,F} \cdot (\mathbf{w}_T \times \mathbf{n}_F).$$

Making $\mathbf{w}_T = h_T \mathbf{curl} \mathbf{v}$, using Cauchy–Schwarz and discrete inverse and trace inequalities, and simplifying leads to (A.5).

We now turn to the estimate on \mathbf{v} , which we decompose as $\mathbf{v} = \mathbf{grad} q + \mathbf{z}$ with $(q, \mathbf{z}) \in \mathcal{P}^{k+1}(T) \times \mathcal{G}^{c,k}(T)$ (see (3.1)). Since $\mathbf{curl} \mathbf{grad} = 0$, we have $\mathbf{curl} \mathbf{v} = \mathbf{curl} \mathbf{z}$ and, using the isomorphism estimate of $\mathbf{curl} : \mathcal{G}^{c,k}(T) \rightarrow \mathcal{R}^{k-1}(T)$ (see [14, Lemma 9]), (A.5) gives

$$\|\mathbf{z}\|_T \lesssim h_T \|\mathbf{curl} \mathbf{z}\|_T \lesssim \|\pi_{\mathcal{R},T}^{k-2} \mathbf{v}\|_T + \left(\sum_{F \in \mathcal{F}_T} h_T \|\mathbf{v}_{t,F}\|_F^2 \right)^{1/2}. \quad (\text{A.6})$$

Upon adding a constant to q , we can assume that q has a zero average on ∂T , and a Poincaré inequality along this boundary thus gives $\|q\|_{\partial T} \lesssim h_T \sum_{F \in \mathcal{F}_T} \|(\mathbf{grad} q)_{t,F}\|_F$. But $(\mathbf{grad} q)_{t,F} = \mathbf{v}_{t,F} - \mathbf{z}_{t,F}$, so (A.6) and discrete trace inequalities lead to

$$\|q\|_{\partial T} \lesssim h_T \sum_{F \in \mathcal{F}_T} \|\mathbf{v}_{t,F}\|_F + h_T \sum_{F \in \mathcal{F}_T} \|\mathbf{z}_{t,F}\|_F \lesssim h_T^{1/2} \|\pi_{\mathcal{R},T}^{k-2} \mathbf{v}\|_T + h_T^{1/2} \left(\sum_{F \in \mathcal{F}_T} h_T \|\mathbf{v}_{t,F}\|_F^2 \right)^{1/2}. \quad (\text{A.7})$$

We now estimate $\pi_{\mathcal{P},T}^{k+1-\eta_T} q$. For all $\mathbf{w}_T \in \mathcal{R}^{c,k+2-\eta_T}(T)$, recalling that $\mathbf{grad} q = \mathbf{v} - \mathbf{z}$ we have

$$\begin{aligned} \int_T q \operatorname{div} \mathbf{w}_T &= - \int_T (\mathbf{v} - \mathbf{z}) \cdot \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F q (\mathbf{w}_T \cdot \mathbf{n}_F) \\ &= - \int_T (\pi_{\mathcal{R},T}^{c,k+2-\eta_T} \mathbf{v} - \mathbf{z}) \cdot \mathbf{w}_T + \sum_{F \in \mathcal{F}_T} \omega_{TF} \int_F q (\mathbf{w}_T \cdot \mathbf{n}_F). \end{aligned}$$

We now use Cauchy–Schwarz inequalities, discrete trace inequalities, (A.7), and (A.6) to deduce

$$\int_T q \operatorname{div} \mathbf{w}_T \lesssim \|\pi_{\mathcal{R},T}^{c,k+2-\eta_T} \mathbf{v}\|_T \|\mathbf{w}_T\|_T + \left[\|\pi_{\mathcal{R},T}^{k-2} \mathbf{v}\|_T + \left(\sum_{F \in \mathcal{F}_T} h_T \|\mathbf{v}_{t,F}\|_F^2 \right)^{1/2} \right] \|\mathbf{w}_T\|_T.$$

This estimate and the isomorphism bound of $\operatorname{div} : \mathcal{R}^{c,k+2-\eta_T}(T) \rightarrow \mathcal{P}^{k+1-\eta_T}(T)$ stated in [14, Lemma 9] yield

$$\|\pi_{\mathcal{P},T}^{k+1-\eta_T} q\|_T \lesssim h_T \|\pi_{\mathcal{R},T}^{c,k+2-\eta_T} \mathbf{v}\|_T + h_T \|\pi_{\mathcal{R},T}^{k-2} \mathbf{v}\|_T + h_T \left(\sum_{F \in \mathcal{F}_T} h_T \|\mathbf{v}_{t,F}\|_F^2 \right)^{1/2} =: h_T \mathcal{N}(\mathbf{v}).$$

Used together with (A.7) in (5.2), this estimate yields $\|q\|_T \lesssim h_T \mathcal{N}(\mathbf{v})$ and thus, via a discrete inverse inequality, $\|\mathbf{grad} q\|_T \lesssim \mathcal{N}(\mathbf{v})$. Since $\mathbf{v} = \mathbf{grad} q + \mathbf{z}$, this bound and (A.6) conclude the proof of (5.3).

Acknowledgements

The authors acknowledge the partial support of *Agence Nationale de la Recherche* grant ANR-20-MRS2-0004 NEMESIS. Daniele Di Pietro also acknowledges the partial support of I-Site MUSE grant ANR-16-IDEX-0006 RHAMNUS. The authors also thank Liam Yemm for his work on the mesh module in HARDCore3D.

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